Precipitation Analysis for a Flood Early Warning System in the Manafwa River Basin, Uganda

by

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ABSTRACT

The communities living in the Manafwa River Basin experience frequent floods threatening their lives and property. Climate change and anthropogenic perturbations to the natural environment increase flooding frequency. This study was performed in conjunction with the Uganda Red Cross Society (URCS) to design a hydrological model for a precipitation based flood forecasting system for the Manafwa River Basin. The hydrological model relates precipitation with flood risk and flood extent. The main input for the model is the basin precipitation. The rainfall data from satellite precipitation estimates produced by the Tropical Rainfall Measurement Mission (TRMM) were used to run the model and observed Manafwa River levels were used to calibrate the model. A calibrated hydrological model is capable of estimating the flood risk given the precipitation and can be used with short term forecasts to trigger an early warning system. Furthermore, the rainfall characteristics and the main climate patterns influencing the basin precipitation were analyzed. Although in recent years the flood magnitude and frequency increased, the average precipitation decreased. Rainfall events are becoming less frequent but more intense. A more intense precipitation rate on a dry soil, with low hydraulic conductivity, generates a higher runoff and can contribute to the increase of the flood events, especially at the beginning of the wet seasons. The influence of the El Niño Southern Oscillation on the precipitation was investigated, but no correlation was found at a local scale.

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Table of Contents

List of Figures

List of tables

1 Introduction

1.1 Study purpose

The Manafwa River basin, in Eastern Uganda, experiences floods that threaten the population. The frequency of these events is reported to have increased in the last decades. A flood warning system enables the population to take precautionary actions and humanitarian organizations to establish emergency preparation and response. Collaboration between the Uganda Red Cross Society and the Massachusetts Institute of Technology initiated to develop a flood warning system for the Manafwa River. In this work the precipitation analysis is presented. The objective is to understand the precipitation patterns that contribute to the flood risk and select the best sources of rainfall records to run a hydrological model for the flood warning system. In order to analyze the precipitation, rain gauges and satellite rainfall estimates are used. At the same time it is advisable to have a broad understanding of the general climate factors and the regional geomorphology influencing the precipitation and its transformation into river flow.

1.2 Study area

The Manafwa River originates from Mount Elgon, a 4000 m extinct shield volcano on the border between Uganda and Kenya. The Manafwa River crosses several districts in Eastern Uganda and joins with other streams to form the Mpologoma River, which terminates in Lake Kyoga (upper left corner in Figure 1). The districts of Manafwa, Mbale, and Butaleja, crossed by the Manafwa River, are prone to frequent floods, especially in recent years.

The area of the Manafwa River catchment basin is 2280 km^2 and it is contained within the districts of Bududa, Mbale, Manafwa, Budaka, Butaleja and Tororo. The only major city in the basin is Mbale, but the basin is densely populated, with a large number of villages, especially near the river and its tributaries.

The topography of the basin has a strong influence on the flood formation. Mount Elgon is the main relief with a maximum elevation greater than 4000 m a.s.l.; its sides are steep and descend abruptly to the plains of Butaleja, at around 1000 m a.s.l., where the variations of the elevation are very small. The presence of the mountain causes orographic lifting and precipitation on the sides of the volcano, often without generating rains on the downstream districts. The rain forms surface runoff that travels on the steep sides of the volcano, often reaching Manafwa and Butaleja without warning.

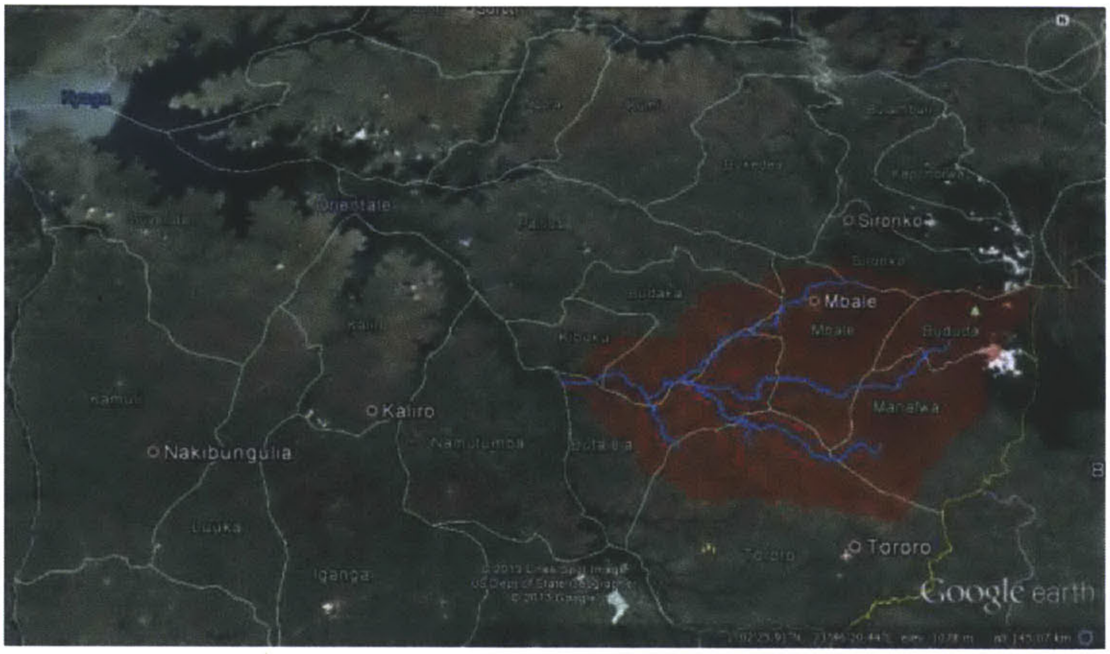


Figure 1 - Google Earth view of the Manafwa River. The highlighted area is the Manafwa basin, the catchment area contributing to Butaleja floods.

The upstream area of the catchment is inside the Mount Elgon National Park, a protected area that is being encroached upon to expand subsistence farming. Most of the remaining territory is dedicated to agriculture, except for the urban area of Mbale which is expanding.

1.3 Floods in the study area

1.3.1 Flood events

The Manafwa basin has been prone to floods in recent years, but it is difficult to reconstruct an historical record because there is not an official database of the flood events in the area.

Usually floods occur in the Butaleja district, but occasionally also upstream in Mbale and Manafwa. In the highlands of Bududa the main problem is flash floods, often causing landslides.

The Red Cross appeals, issued to collect the funds for the post-emergency interventions, can be a first step to reconstruct the most important events of the recent years. In Table 1 a list of the events that involved the Manafwa basin retrieved through the Red Cross appeals is reported.

Table 1 - Flood records retrieved from the Red Cross appeals

Date	Involved Districts	Type of event	Affected Households
July 2011	Bududa	Landslide	NA
	Butaleja	Flood	231
	Mbale	Flood	45
March 2010	Bududa	Flash Flood, Landslide	206
	Butaleja	Flood	1204
	Mbale	Flood	238
	Manafwa	Flood	56
	Budaka	Flood	211
July-Sep 2007	Bududa	Flash Floods, Landslides	560

The Uganda Red Cross Society has been able to document rainfall-related events that affected the region.

Table 2 - Flood events as recorded by the Uganda Red Cross Society in the Manafwa River basin

Year	Parish	Village	No. of killed
2012	Tindi	Tindi	-
2012	Kanyenya	Kanyenya A	-
2010	Muyago	Wega, Wapala, Namahere, Paya, Leresi and Butesa	6
2010	Dhoho	Kooli	3
2010	Kapisa	Manafa	1
2009	Dhoho	Muhuyu	1
2008	Lubembe	Nandelema	3
2007	Bufuja	Nasogo	2

Another source of information is the EM-DAT, the International Disaster Database, which is not complete, but offers an organized list of events:

Table 3 - Floods recorded in the EM-DAT database that affected the Manafwa basin

Year	Districts	Start month	End month	No. killed	No. affected	No. homeless
2011	Mbale Butaleja	8	9	27	63075	0
2007	Bududa, Mbale, Manafwa	8	10	29	435070	282975
2006	Butaleja	10	12	0	4000	0
2003	Mbale	7	7	20	700	0
2002	Mbale	4	5	17	760	0
1997	Tororo, Mbale	11	11	100	150000	3500

Other information was retrieved through unofficial sources on the Internet, such as television channels and newspapers.

Table 4 - List of Flood events retrieved through unofficial sources

Date	Involved Districts	Type of event	Source
August 2012	Butaleja	Flood	TVUganda
	Manafwa	Flood	NTV Uganda
June 2012	Bududa	Flash Flood, landslide	Al Jazeera
May 2010	Butaleja	Flood	NTV Uganda
March 2010	Butaleja	Flood	NTV Uganda
	Bududa	Flash Flood, landslide	NTV Uganda

The last source of information is the local community. In January 2013, 25 people in 5 different villages in Butaleja were interviewed to collect their memories and their estimates of the flood problem in their village. Among the other questions, the villagers were asked when the worst floods they remember occurred. The answers are reported in Table 5, where the worst floods are bolded.

Table 5 - Worst floods that people interviewed in five villages in the Butaleja Distict can remember.

Tindi Village	Masulula Village	Doho village	Nahasalagala Village	Wagabono Village
February 2012	**April 2012**	**November 2012**	**June 2012**	**2012**
April 2012	1997	1997	April 2012	1997
May 2012	**1994**	1962	**1997**	**1961**
April 2011	1960			

Another important outcome of the surveys is the concept of flood in the local communities' perspective. Because the flood frequency is so high, several interviewed people inferred they only consider floods to be the events with a water depth above the knee. Considering this fact, the number of floods that actually occurred in the area may be greater than those reported.

Although all the data are not in perfect agreement, it is possible to infer that major floods occurred in 1997, in 2010 and in 2012, but a large number of minor events occurred almost yearly, especially in the recent years.

1.3.2 Flood frequency

The variation of the flood incidence in the years studied is an important issue. From the sources cited above it could not be established if the flood frequency or magnitude have changed during the years studied. The Red Cross reports, the EM-DAT records and the Internet based sources cover just the recent years and their accuracy cannot be assessed. In the last five years reported events are more numerous, but it is probably because of better information diffusion rather than a frequency variation of the events. The memory of residents can be distorted and related to the age of the interviewed subjects; nonetheless, it is common opinion among the population that the frequency of the floods has increased in the recent years.

The Water Resources Department of the Ministry of Water and Environment in Uganda has recorded the river stages in Busiu, a city located in the middle of the basin, near a bridge connecting the Mbale district to the Manafwa district. The exact position in the basin is shown in Figure 2.

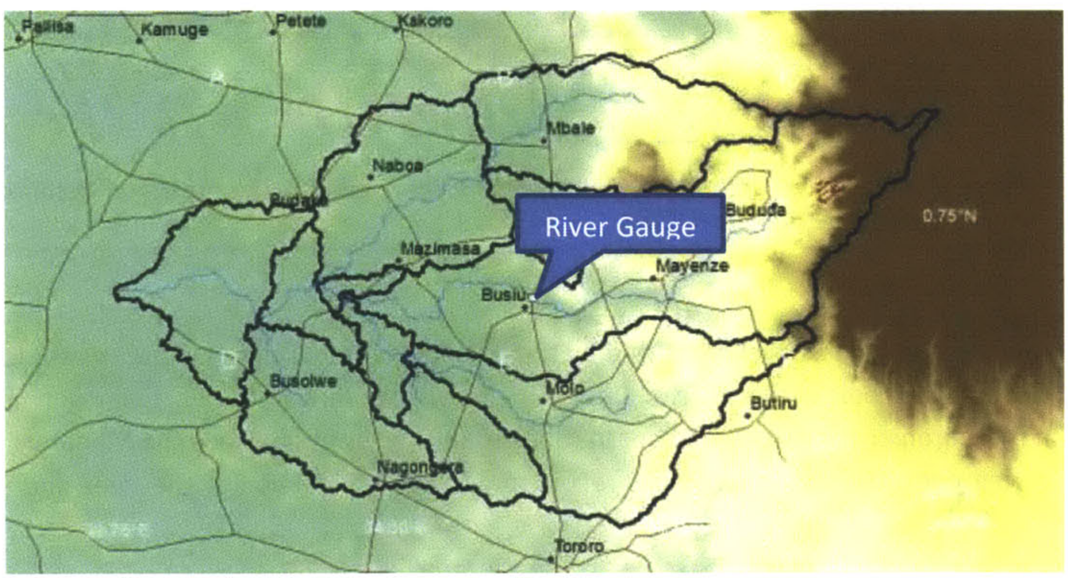


Figure 2 - River Gauge position inside the Manafwa River basin

The river stages were recorded from March 1997 to June 2008, with a gap between November 1997 and June 1999. The gap is probably because of a failure of the system during the 1997 flood. The records indicate that the frequency and magnitude of high-water-level events in the Manafwa River is increasing. The transformation of a high-water-level event at the river gauge into a flood in the Butaleja District depends on the condition of the river bed and on the land use downstream.

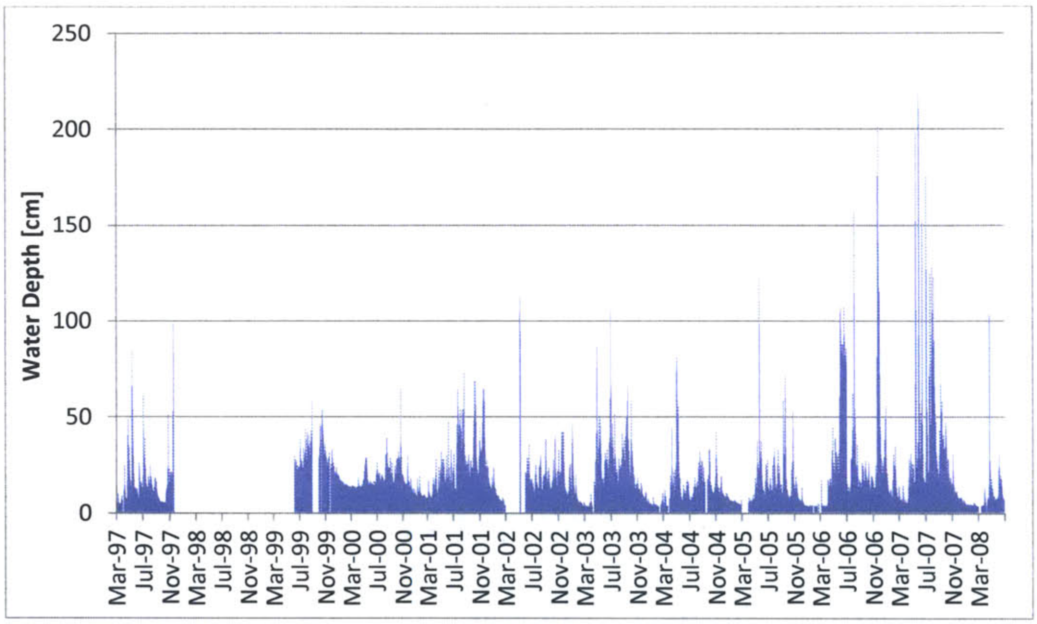


Figure 3 - Water level of the Manafwa River in Busiu, as recorded by the Water Resources Department's river gauge

From the reported water level measured by the river gauge in Busiu, the winter water level is very low, often below the 20 cm. During a site visit in January 2013, two river cross section measurements were carried out in the Manafwa River basin. Since the Manafwa is a meandering river, the water lever was recorded in a straight section of the river and in a curve.

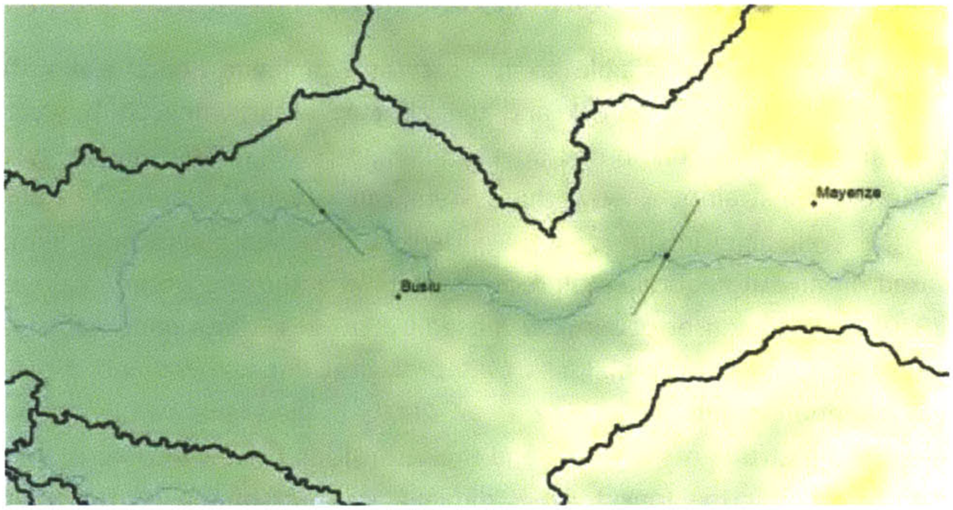


Figure 4 - River cross sections position. The one on the left is in a curve, downstream; the one on the right is in a straight section, upstream.

The instrument in Busiu is on the point bar side of the river meander. The values measured by the river gauge are consistent with the values measured in the river cross section; this can be seen by observing the water depth on the left side of Figure 1; the depth of the water between 0 m and 3 m from the bank is in the range of 0 cm – 20 cm deep which is consistent with values reported by the river gauge in the winter months.

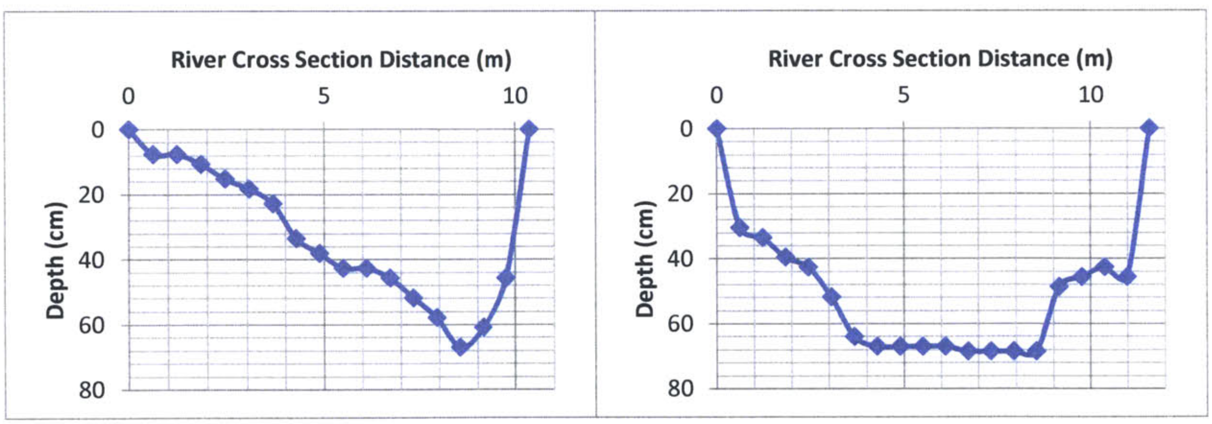


Figure 5 - The river cross sections as measured. The cross section on the left is a meander, the cross section on the right is a straight segment. In both the flow is toward the page.

1.4 *The importance of an early warning system*

A flood early warning system is able to forecast an imminent flood, elaborate the information to predict the level of risk and the affected areas, and communicate the information to authorities, population or other stakeholders. The design of the system is subject to different constraints. Firstly, the system can rely on different technologies, depending on the availability in the region. Windarto J. designed a system in Semarang, Indonesia, based on an automatic rainfall recorder and an automatic water level recorder (Windarto, 2010). A wired sensor network was used by Aziz et al. for a flood early warning system conceptualized with the Malaysia's Meteorological Department and the Pahang Department of Irrigation and drainage (Aziz, et al., 2009). In the Manafwa River region the availability of ground instruments is scarce and the installation of new devices is advisable, but their maintenance for the long term is difficult. In areas of the World where the reliability of ground sensors is low, remote sensing and GIS products can be used to obtain geographical and meteorological information. In a flood early warning system in the Madarsoo basin, Iran, Azari et al. used satellite images to classify clouds in order to forecast rainfall, soil and land use maps to calculate the Curve Numbers, indicators of soil hydraulic conductivity, and river GIS geometry to model runoff and flooding scenarios (Azari, et al., 2008).

Another constraint is the type of flood risk to forecast. Floods can be generated by different natural factors like tropical rainfalls, monsoons, and hurricanes surges, or artificial factors like the failure of dams and dikes. The design of a flood early warning system is strongly influenced by the type of flood risk, both in the input data acquisition and in the hydrological modeling. For example, precipitation can have different patterns in different regions, requiring a modeling approach on diverse temporal and geographical scales.

The river flow rate and the flooded areas can be forecasted with more or less complex models. The complexity of a model helps in obtaining precise and reliable results, but requires a larger number of parameters and a longer processing time (Silvestro, et al., 2013). Where the availability of data is limited, like in Eastern Uganda, the precision of a complex model is counterbalanced by the uncertainty of the parameters; therefore a relatively simple approach was carried out in this study, using HEC-HMS and HEC-RAS, the models distributed by the U.S. Army Corps of Engineers.

Another crucial element of an early warning system is the message delivery. Once the flood risk is modeled it must be communicated to stakeholders, authorities and population. In 2008, the International Federation of Red Cross and Red Crescent Societies (IFRC) has used seasonal forecasts, predicting a particularly wet July-September rainy season, to issue an emergency-based appeal for the first time ever. The anticipated funds allowed the Red

Cross to preposition emergency commodities in the local warehouses, update flood contingency plans, and communicate the risk locally (Tall, et al., 2012). Although the operation can be considered successful, reducing drastically life losses, the time to deliver emergency items, and costs of the humanitarian response (IFRC, 2008), some communication issues have been observed:

> "language, content, and format of forecasts compound the poor accessibility of climate information. Indeed, these aspects of the forecast are not adequately considered to ensure forecast comprehension by community-level users. (...) Also, the probabilistic nature of seasonal forecasting is prone to misinterpretation and confusion if probabilities are translated into deterministic statements and warnings or otherwise manipulated." (Tall, et al., 2012).

Problems related to the low spatial resolution of seasonal forecasts were also perceived.

The model used for the Manafwa River basin is deterministic and specific for the local scale. To reduce the uncertainty, the warning system will be based on short term precipitation forecasts. The output will be a map of the areas predicted to be flooded, with the forecasted water depth represented as a color gradient. This type of communication is easy to interpret and is not subject to language issues. Additionally, the Red Cross/Red Crescent Climate Center in Kampala will act as a filter to interpret and spread the information.

Consistent with the approach of Aziz et al. and Windarto did (Aziz, et al., 2009) (Windarto, 2010), the Manafwa flood early warning system will use SMS and web technology to maintain communications between the system, the Climate Center and the local Red Cross volunteers on the territory. Although the power network and the Internet network are poor, the cell phone services and the 3G services are reliable in the Manafwa area.

1.5 *The influence of ENSO*

The Manafwa River flood early warning system is proposed specifically for a small region and with the ability of predicting floods with a short time lag. Nevertheless, it is important to understand if the seasonal weather can be broadly forecasted looking at global meteorological phenomena. The tropical climate of Uganda is mainly influenced by the Inter-Tropical Convergence Zone (ITCZ) that generates two rainy seasons a year crossing the equator from north to south and from south to north; the first wet season is between March and May, the second is between September and November. The March-April-May (MAM) rainy season is usually more intense.

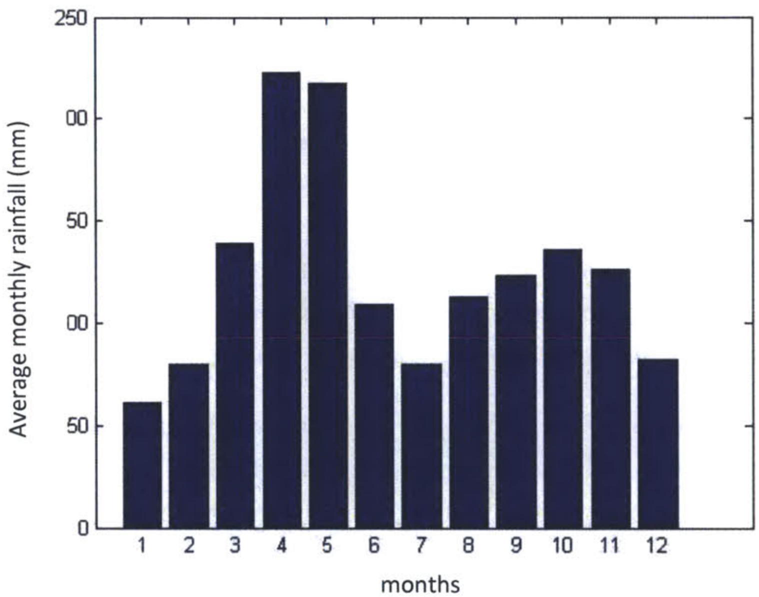


Figure 6 - Average monthly precipitation on the Manafwa River basin from 2006 to 2012

Other global phenomena can have influences on the precipitation in Uganda. The most studied is the El Niño Southern Oscillation (ENSO), a periodical oscillation of sea-level, temperature, atmospheric pressure, and rainfall on the eastern and the western Pacific Ocean coasts. The ENSO oscillation is characterized by two different phases, El Niño and La Niña. During an El Niño phase, the water of the Eastern Pacific is warmer, and more intense precipitations occur. During la Niña the water warming and the intense precipitations occur on the Western side of the Pacific Ocean. El Niño episodes usually occur every 3-5 years and lasts for 9-12 months (National Oceanic and Atmospheric Administration, 2007). The influence of the ENSO is not limited to the geographic areas on the Pacific Ocean; ENSO affects the climate of multiple regions in the World. Several studies assessed the influence of the ENSO in different geographic areas. Ropelewski and Halpert identified an Eastern

Equatorial African region (EEQ), including Uganda, where the El Niño phase causes greater than normal precipitations between October and April (Ropelewski & Halpert, 1987). In 2004, Ntale and Yew Gan observed that "Southern Uganda and much of the Lake Victoria basin show some significant positive ENSO response for November, December, and January" (Ntale & Thian Yew Gan, 2004). In 2007, Wardlaw et al. developed a specific study in Uganda, observing that the Net Basin Supply (NBT) of Lake Victoria is higher during the El Niño events, in the October-November-December-January season (Wardlaw, et al., 2007).

Despite the evidences presented in the cited papers, the relation between ENSO and general Eastern Equatorial Africa's climate does not imply a correlation between ENSO and the local precipitation in the Manafwa River basin. The relation is assessed in Chapter 5.

2 Precipitation observations

In this work two different sources of rainfall information were used: rain gauges and satellite precipitation estimates. These two data sets were compared to assess their reliability and the result was considered to provide the hydrological model with the best possible estimate of the daily precipitation on the Manafwa River basin. The precipitation information was also used to analyze the influence of the El Niño Southern Oscillation (ENSO) on the seasonal precipitation characteristics.

2.1 Rain Gauges

Rain gauges are usually the base source of rainfall data, but in Uganda the availability of information is limited. The number of active rain gauges in the territory is small and often it is not possible to have free access to the rain gauge records. For this study, three sources of ground measurements were used:

1. The first dataset was recorded by a rain gauge in the Bududa District. The data is from January 2009 to June 2012. The dataset was provided by the Red Cross.
2. The second dataset is from a rain gauge in Buginyanya, a town outside the basin, but sufficiently close to the northern boundary to be relevant. It recorded daily precipitation values from 2006 to 2010.
3. The third dataset was recorded by a rain gauge in Tororo, outside the basin, but near the southern boundary of it. The records are between 1929 and 1986 (National Oceanic and Atmospheric Administration, 2013).

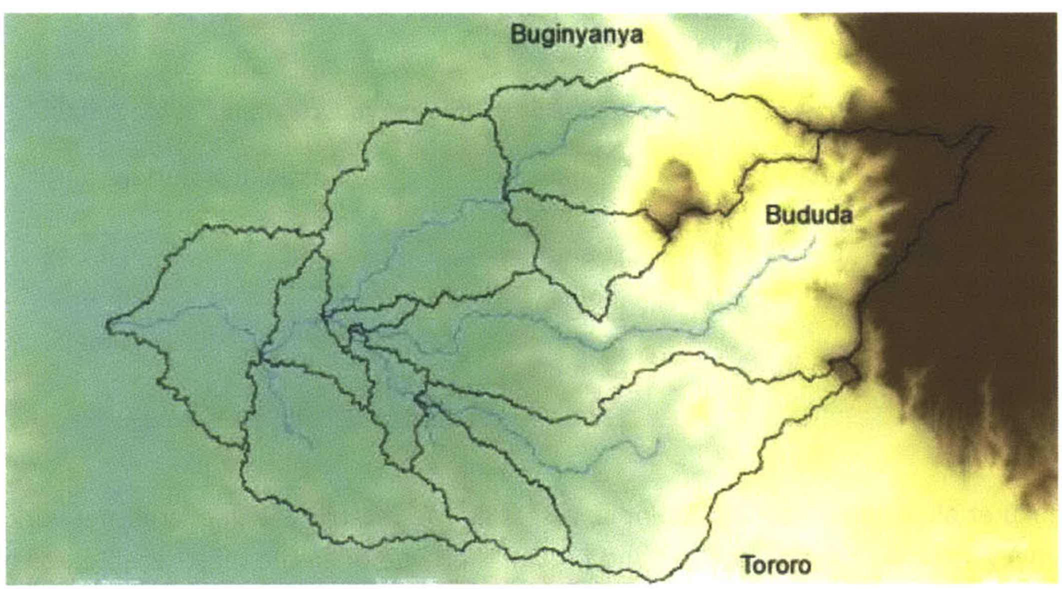


Figure 7 - Rain gauges position in respect of the basin

The records from the rain gauges in Bududa and in Butaleja cover short, but recent periods of time, and can be easily compared with the satellite records; the data from the rain gauge in Tororo, instead, can be useful for long term analyses.

2.2 Satellite observations

The sources of rainfall estimates made with satellite tools are abundant, but with different characteristics. Studies were done to understand the reliability of satellite data in different areas. In 2007, Dinku et al. analyzed a variety of products dividing them into two categories: high-resolution products and low-resolution products (Dinku et al., 2007). Since the Manafwa River basin is relatively small, compared to the satellite resolution, the analysis of the second ones is of particular interest for this work. In the second group Dinku et al. have considered:

- The 1 Degree Daily Combination (1DD) produced by the Global Precipitation Climatology Project (GPCP), (Global Precipitation Climatology Project, 2013)
- The Africa Rainfall Estimate (RFE 2.0) produced by the National Ocean and Atmospheric Administration's Climate Prediction Center (NOAA-CPC), (Climate Prediction Center, 2013)
- The CPC Morphing technique (CMORPH) by the National Ocean and Atmospheric Administration's Climate Prediction Center (NOAA-CPC), (Climate Prediction Center, 2013)
- The Tropical Rainfall Measurement Mission (TRMM) daily product (3B42), (Tropical Rainfall Measuring Mission, 2013), from the NASA Goddard Space Flight Center.
- The Tropical Application of Meteorology using Satellite and other data (TAMSAT) estimates, (University of Reading, 2013)

Table 6 - Characteristics of the main satellite precipitation products (Dinku et al., 2007):

Product	Temporal Resolution	Spatial Resolution
GPCP-1DD	1 day	1.0°
RFE 2.0	1 day	0.1°
CMORPH	3 hours	0.25°
TRMM-3B42	3 hours	0.25°
TAMSAT	10 days	0.50°

Dinku et al. analyzed data in Ethiopia, assessing the reliability with a large network of rain gauges. In that analysis, TAMSAT and CMORPH proved to be the most reliable, followed by TRMM, then GPCP-1DD; RFE 2.0 performed poorly on the study area (Dinku et al., 2007).

A study was conducted by Asadullah et al. in 2010, comparing the performance of five satellite products over Uganda. The analysis considered RFE 2.0, TRMM-3B42, CMORPH, TAMSAT and PERSIANN, a system from the University of California, Irvine (UC Irvine, 2013). Asadullah et al. conducted the study in different regions in Uganda, and the analysis on the Mt. Elgon region is particularly interesting for the purpose of the present work. On Mt. Elgon, TRMM-3B42 performed better than the other products, maintaining good efficiency despite the high elevation (Asadullah et al., 2010).

For this reason, TRMM-3B42 was selected for this study too; it showed good performances in the Mt. Elgon region and has good resolution in time and space. The Tropical Rainfall Measurement Mission, from the NASA Goddard Space Flight Center, uses two different sensors to estimate precipitation. Where available the rainfall estimate is obtained from passive microwave (PMW) observations; where the PMW is missing the precipitation is estimated from PMW-calibrated infrared (IR) data (Asadullah et al., 2010).

2.3 Comparison and statistics

2.3.1 TRMM, Bududa and Buginyanya records

In order to understand if the rain gauge information is reliable, it can be compared with TRMM data. The daily precipitation values estimated by TRMM in the 0.25°x0.25° cell containing a rain gauge were compared with the daily values registered by that rain gauge. This comparison was performed with the rain gauges in Bududa and Buginyanya. The result obtained is not positive: there is no correlation between TRMM and either rain gauge in Bududa or Buginyanaya.

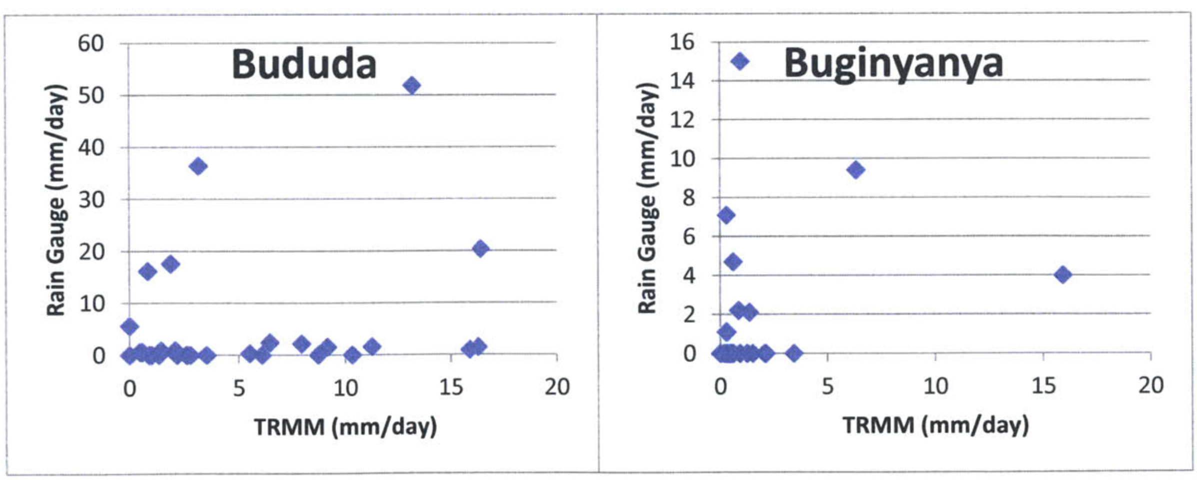


Figure 8 - Example of TRMM-Rain Gauge correlation for the rain gauge in Bududa and Buginyaya during two sample months

While the TRMM data are internationally used, tested and validated, the rain gauge datasets from Bududa and Buginyanya are locally recorded with no validation. The rain gauges are not automatic and the precipitation values are recorded daily on hardcopy archives. It is difficult to monitor who accomplishes this task every day and how conformed to standards every measurement is. To be sure that the critical flawed elements are the rain gauges records, a simple analysis was performed: the precipitation records were cumulated, to provide an estimate of the yearly precipitation.

Table 7 - Yearly precipitation on Bududa as reported by the rain gauge in Bududa and by the TRMM

	2010	2011
Bududa Rain Gauge	11.615 m	5.545 m
TRMM data	1.543 m	1.465 m

Table 8 - Yearly precipitation on Buginyanya as reported by the rain gauge in Buginyanya and by the TRMM

	2006	2007	2008	2009	2010
Buginyanya Rain Gauge	3.535 m	4.652 m	2.188 m	1.527 m	1.990 m
TRMM data	1.831 m	1.604 m	1.491 m	1.248 m	1.399 m

The TRMM data shows a slightly decreasing trend, analyzed in Chapter 3, but maintains a reasonable order of magnitude, between 1.25 m and 1.83 m of rainfall per year. These values are reasonable and consistent with the tropical climate of the country. Both the dataset in Bududa and in Buginyanya show unrealistic values. Even considering the tropical climate of Uganda, the yearly precipitation cumulates should remain below 2 m per year. Furthermore, there is a considerable change in order of magnitude in the reported years. For example, the Bududa rain gauge registered 11.6 m of rain in 2010, but just 5.5 m in 2011. This excludes a possible misinterpretation of units. If the Bududa records were reported using the wrong units, all the values would be off of the same factor.

2.3.2 Tororo dataset

Tororo's dataset differs from those of Bududa and Buginyanya. Firstly, the records are from 1929 to 1986, therefore it is impossible to compare it with satellite estimates because satellite data from those years does not exist. Secondly, the dataset is distributed internationally by the National Oceanic and Atmospheric Administration (NOAA) and it is consistent with the standards of the Global Historical Climatology Network (National Climatic Data Center, 2013). The yearly values of precipitation were calculated for Tororo's dataset too and are reported in Table 9. The dataset shows a consistent data gap in 1984; therefore the dataset has been considered reliable for consecutive years between 1929 and 1983.

Table 9 - Yearly precipitation in Tororo as recorded by the rain gauge

Year	Rainfall (m)	Year	Rainfall (m)	Year	Rainfall (m)	Year	Rainfall (m)	Year	Rainfall (m)
1929	1,569	1940	1,4197	1951	1,6369	1962	1,7538	1973	1,0176
1930	1,415	1941	1,5283	1952	1,4927	1963	1,7917	1974	1,2436
1931	1,661	1942	1,4695	1953	1,0529	1964	1,6365	1975	1,615
1932	1,5787	1943	1,2151	1954	1,2829	1965	1,3029	1976	1,3434
1933	1,4189	1944	1,3319	1955	1,3924	1966	1,5285	1977	1,9684
1934	1,5643	1945	1,2288	1956	1,4177	1967	1,5806	1978	1,2852
1935	1,6254	1946	1,546	1957	1,4261	1968	1,6847	1979	1,2792
1936	1,3781	1947	1,4801	1958	1,2689	1969	1,6115	1980	1,0338
1937	1,3162	1948	1,2097	1959	1,3453	1970	1,7024	1981	1,4031
1938	1,1375	1949	1,1122	1960	1,638	1971	1,4875	1982	1,5567
1939	1,0811	1950	1,3303	1961	1,9795	1972	1,6972	1983	1,349

The Tororo records are consistent with the values registered by TRMM in 2006-2012, never below 1 m/yr and never above 2 m/yr.

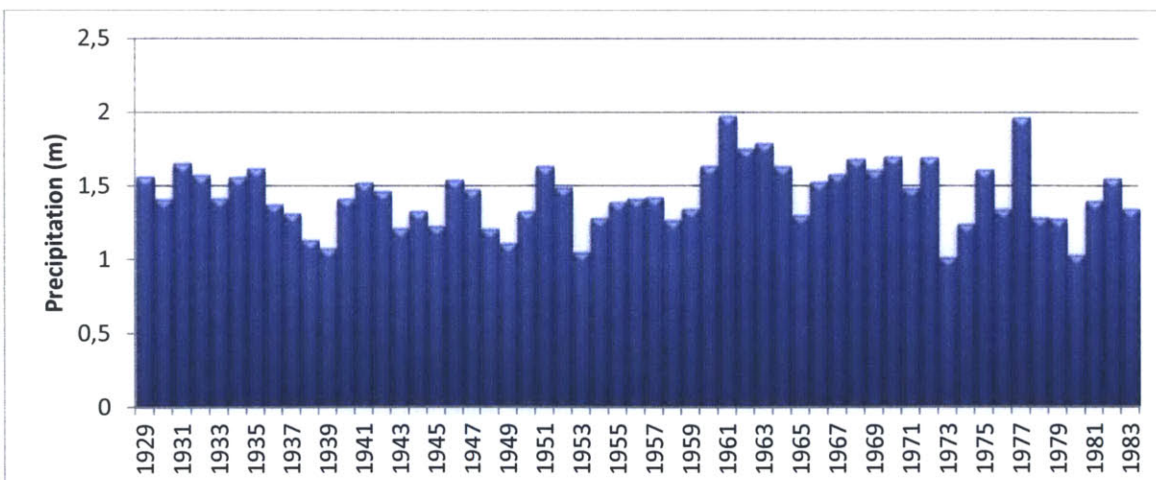


Figure 9 - Yearly Precipitation in Tororo as registered by the Rain Gauge

2.4 Analysis of the results

The TRMM data and the dataset from Tororo seem reliable and were used in this study. The datasets from Bududa and Buginyanya, instead, cannot be used. For the short term analysis and for the hydrological model of the basin the TRMM data was used, but no calibration was possible. For the long term analysis the records from Tororo are considered between 1929 and 1983.

Although TRMM proved to be a reliable and validated source of rainfall estimates, the calibration with rain gauges was advisable. Indeed the dataset does not show recorded values, it shows estimates, which implies a physiological error. Furthermore, the estimates are averaged on 0.25°x0.25° cells, quite large in respect to the dimension of the basin. Therefore TRMM can be considered to have a general representation of the precipitation variation during the days and the months, but will not be able to represent local variability inside the basin.

3 Precipitation trend

The increasing flood frequency and magnitude is often explained by local communities as a consequence of climate change increasing precipitation; however, the explanation may be more complex. In Uganda while climate change has been observed in recent years, land use change has had a role in flood intensification too. Although one might assume that climate change has led to increased precipitation and flooding, this is not what is happening in the region. In 2012 the U.S. Geological Survey (USGS) issued a report analyzing the climate trends in Uganda. From the report it can be seen that precipitation is decreasing during the rainy seasons and the temperature is increasing (USGS, 2012).

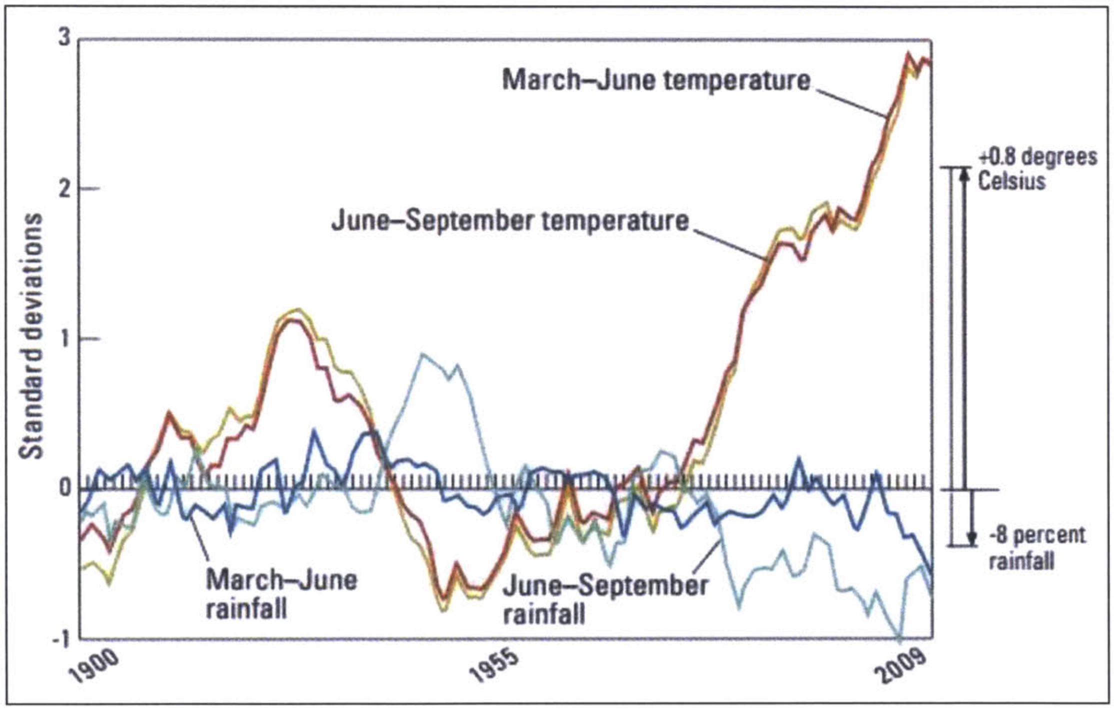


Figure 10 - 10-year running average of the precipitation (blue) and the temperatures (orange) during the two rainy seasons (USGS, 2012)

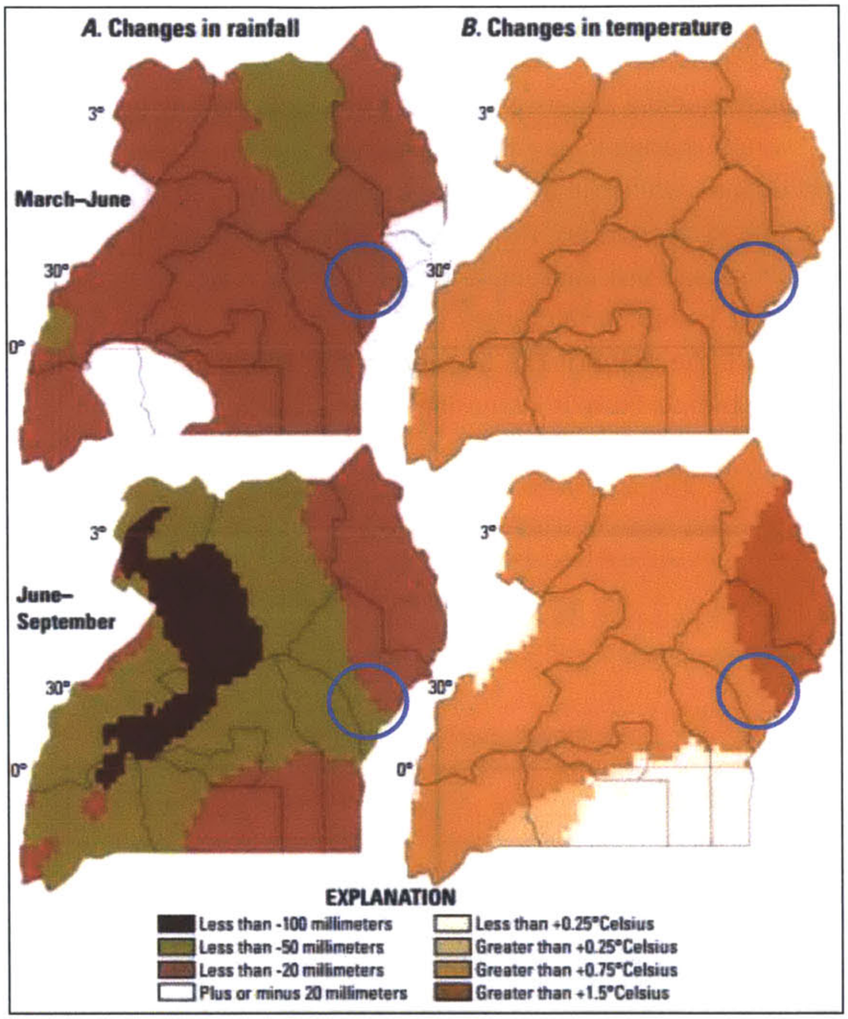


Figure 11 - Variation in precipitation and temperature between the period 1960-2009 (observed) and 2010-2039 (projected) for the two rainy seasons (USGS, 2012). The blue circles identify the position of the Manafwa basin.

In the Manafwa River basin the trend is similar. Analyzing the precipitation data recorded by TRMM in the recent years (2006-2012) on the basin, the trend is decreasing as well (Figure 12).

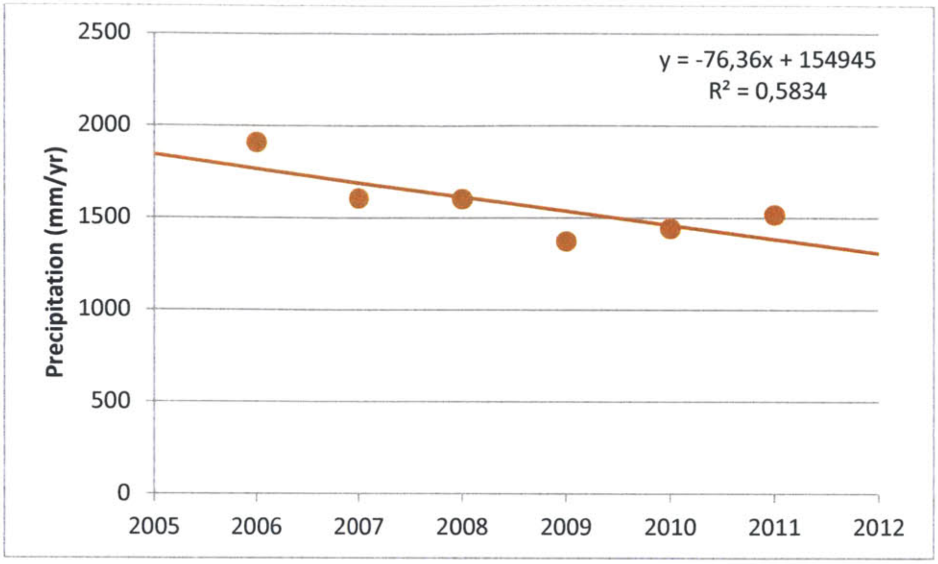


Figure 12 – Average yearly rainfall between 2006 and 2011. A linear trendline is added to show the decreasing trend.

The same analysis can be carried out separating the months in different seasons: March-April-May (MAM), June-July-August (JJA), September-October-November (SON), and December-January-February (DJF). The result is interesting: the largest decrease in precipitation is observed in the DJF dry season, while the major wet season, MAM, is almost constant in time (See Annex 1- Precipitation trends in the four different seasons). A possible explanation is the increase of the high-intensity events' magnitude, mainly in the wet season.

If the precipitation on the region is decreasing, why are the floods increasing? Three main explanations can be identified:

1. The land use changed during the years: forests were transformed in crops and urban areas expanded, increasing the impervious areas of the basin and reducing the infiltration capacity.
2. On average the rainfall is decreasing, but the peaks are more intense.
3. In a clay-rich soil, the decrease in precipitation makes the terrain drier, lowering the hydraulic conductivity and therefore the infiltration rate. The water falling during heavy rain events can infiltrate less and must runoff, generating a higher surface flow.

A more in depth analysis of the land use change impact on the floods in the Manafwa River basin is presented in Fidele Bingwa's thesis, Massachusetts Institute of Technology, 2013 (Bingwa, 2013).

Evaluation of the high-intensity events was performed using the TRMM data between 2006 and 2011. Alpert et al. performed a study of high-intensity precipitation events in the Mediterranean region, considering the recorded daily rainfall values above 128 mm/day (Alpert, et al., 2002). Since TRMM provides precipitation estimates averaged on a large area, the daily precipitation peaks cannot be as intense as that registered by point measurements. For this reason, the days when the precipitation is above 30 mm/day were classified as high-intensity events in this study. The 30 mm/day threshold was selected to maintain a small number of extreme events per year, but sufficient to make statistical analysis meaningful. In Figure 13 the number of intense events per year and the maximum daily value registered each year are compared.

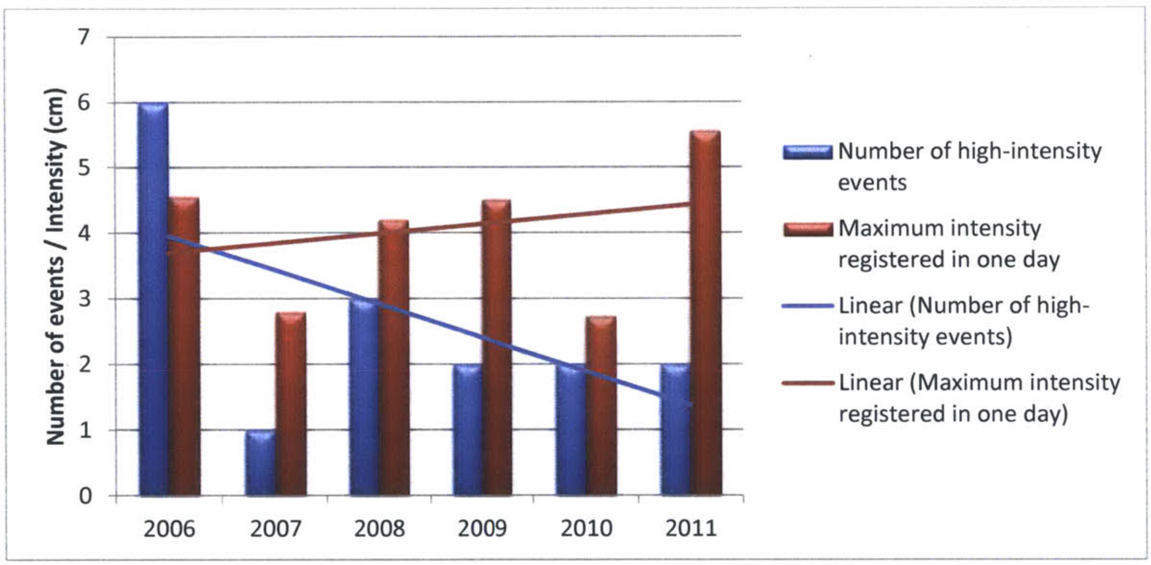


Figure 13 - The number of high-intensity events is compared with the intensity of the maximum registered event each year

The number of intense events is decreasing, but their intensity is increasing. The presented data describes how the climate in the basin, as in the rest of Uganda, is getting drier, but the rainfall peaks are more intense. A similar effect was observed on the Mediterranean too (Alpert, et al., 2002). In recent years, rainfall occurs with higher precipitation rate and the terrain, on average more dry, has a lower infiltration rate (Maidment, 1993).

This effect is particularly intense for clay-rich soils and in the Manafwa Basin the clay content is high in most of the soil layers (FAO, 2007).

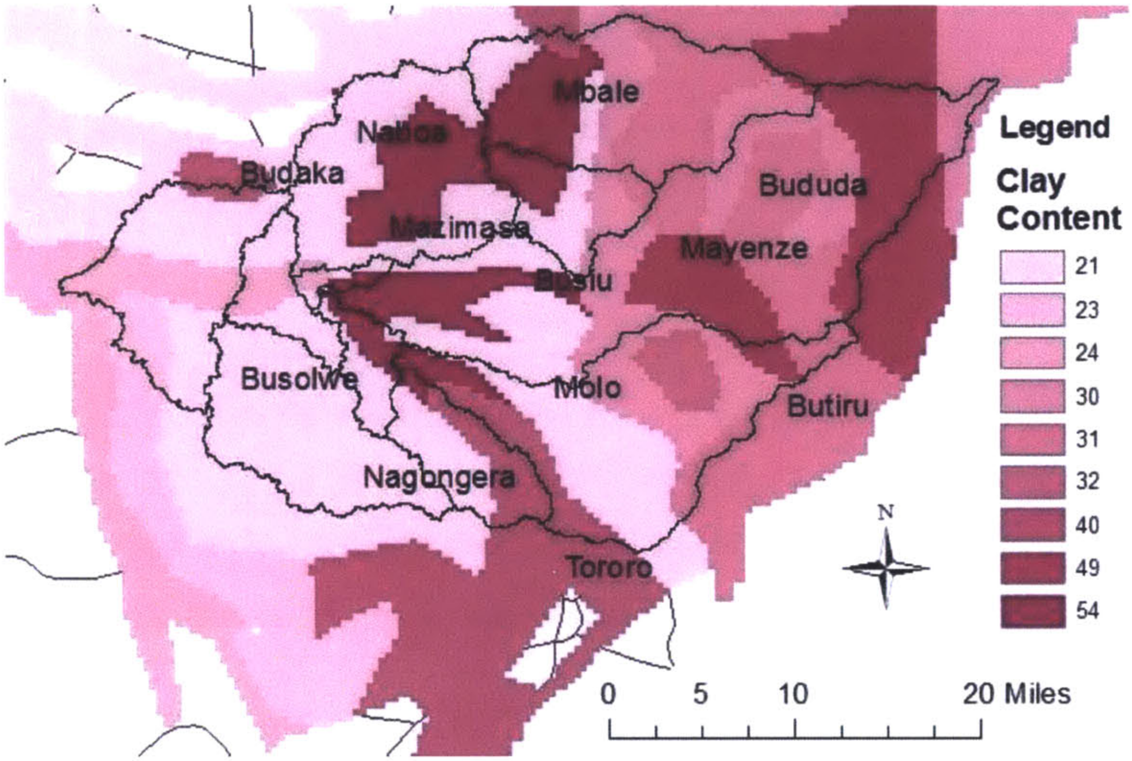


Figure 14 - Soil content in the Manafwa basin (FAO, 2007)

The result is that the fraction of rainfall transformed into runoff is increasing and therefore the floods are more numerous and intense. An indication of this effect is the large number of floods at the beginning of the wet season.

Table 10 - Recorded floods that occurred at the beginning of the wet seasons

August 2012
July-September 2011
March 2010
July-September 2007
July 2003

4 Flood forecasting

4.1 *Model used: HEC-HMS and HEC-RAS*

The flood early warning system design is based on a hydrological model that transforms precipitation data into a basin hydrograph and subsequently the hydrograph into downstream river water depth, which can be mapped to represent this quantitative information in a graphical form. To develop the model the hydrological tools developed and freely distributed by the U.S. Army's Corps of Engineers, HEC-HMS and HEC-RAS, were used.

HEC-HMS (Hydrologic Engineering Center – Hydrologic Modeling System) is a system able to simulate infiltration-runoff processes in river basins, and to calculate the flow generated, given the precipitation and the characteristics of the basin (land use, soil type, elevation, etc.). HEC-HMS offers several standard model choices with which to calculate runoff and infiltration. For the Manafwa River model the selected method is the Soil Conservation Service (SCS) Curve Number (CN) method; the SCS CN method is simple, well established and widely accepted. It is based on the calculation of the Curve Number, a parameter between 0 and 100 coupling the soil properties and the land use, in every sub basin. It represents the infiltration capacity of the sub basin. HEC-RAS (Hydrologic Engineering Center – River Analysis System) is able to calculate the variation of water level in a given waterway at different time steps. HEC-RAS relies upon the hydrograph calculated by HEC-HMS and the elevation and geometry of the river.

To prepare the input data for HEC-HMS and HEC-RAS, other toolboxes for the Environmental Systems Research Institute (ESRI)'s geographical information system platform, ArcGIS, are available (U.S. Army Corps of Engineers, s.d.). Additional information about the developed model can be found in the thesis by Yan Ma, Massachusetts Institute of Technology (Ma, 2013).

4.2 *Precipitation data used*

Because rain gauge data are not reliable, the hydrological model was run using TRMM daily data. HEC-HMS normally requires one or more rain gauges values per sub basin, thus TRMM records were processed to determine a daily precipitation value for every sub basin. Overlapping the basin shape file with a TRMM file, the daily values of precipitation for every sub-basin were calculated as the average of the TRMM cells that the sub-basin contains, approximately weighted on the respective areas.

For Example, looking at Figure 15 the area of the sub basin labeled W200 is approximately defined by the sum of $\frac{2}{3}$ of TRMM cell D and $\frac{1}{3}$ of TRMM cell E. Therefore the precipitation value in sub basin W200 is calculated as:

$$P_{W200} = \frac{1}{3}E + \frac{2}{3}D$$

With E = precipitation value in TRMM cell E, D = precipitation value in TRMM cell D. Similarly an approximated equation was considered for every sub basin. The equations are reported in Table 11.

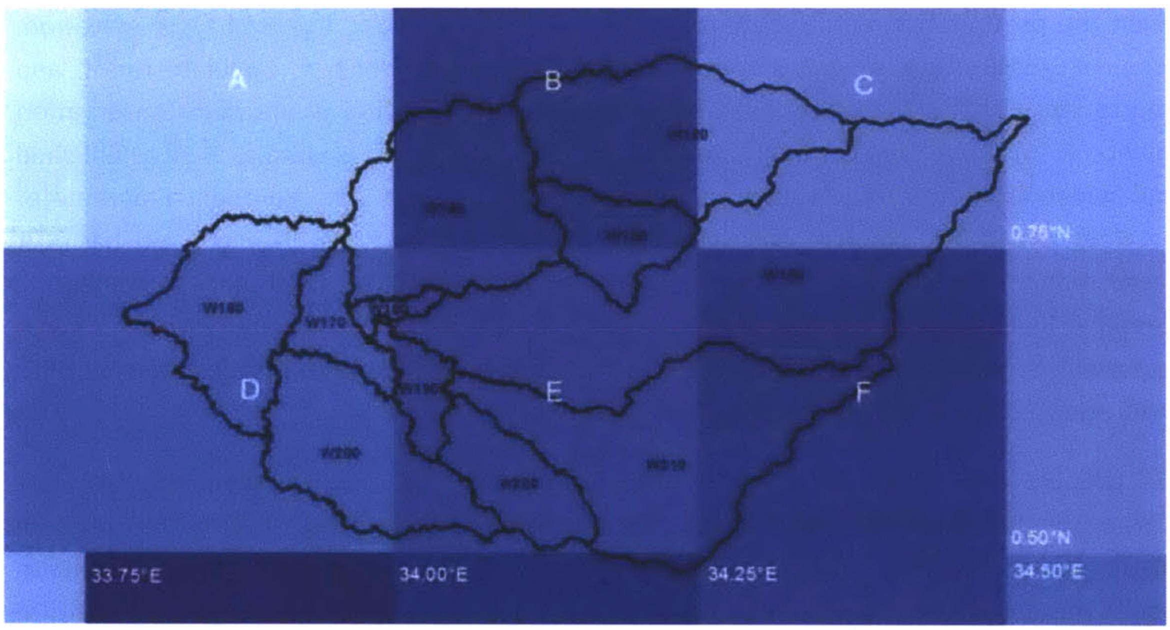


Figure 15 - The sub basins are identifies with values fromW120 to W220, with step 10, by HEC-HMS. The TRMM cells considered for the model calibration have been named from A to F.

Table 11 - The average of the TRMM cells contained in every sub basin, weighted on the areas, were used to calculate the precipiation values for every sub basin as follows

Sub-basin	Equation
W120	2/3 B + 1/3 C
W130	3/7 E + 4/7 B
W140	1/21 D + 2/21 A + 3/21 E + 15/21 B
W150	1/3 E + 1/3 F + 1/3 C
W160	1/8 A + 7/8 D
W170	D
W180	1/2 D + 1/2 E
W190	1/15 D + 14/15 E
W200	2/3 D + 1/3 E
W210	1/2 E + 1/2 F
W220	E

The operation was repeated on the daily TRMM files, from January 1st, 2006 to June 30th, 2012. The result is a record of daily rainfall estimates for every sub-basin, which was input to the model in lieu of rain gauge measurements.

5 El Nino influence on precipitation

5.1 Relationship analysis

The methods used to test the relationship between ENSO and precipitation are various and they can be more or less complex. A commonly used technique is the study of the precipitation signal frequency, to individuate the ENSO component (Ropelewski & Halpert, 1987) (Ropelewski & Halpert, 1988) (Camberlin & Philippon, 2001) (Ntale & Thian Yew Gan, 2004). Another technique is proposed by Wardlaw et al., using the Southern Oscillation Index (SOI). The SOI is a standardized index measuring the monthly mean sea level pressure differences between Darwin, Australia, and Tahiti (National Oceanic and Atmospheric Administration, 2013).

$$SOI = \frac{Standardized\, Thaiti\, SLP - Standardized\, Darwin\, SLP}{Monthly\, Standard\, Deviation}$$

$$Standardized\, Thaiti\, SLP = \frac{Actual\, Tahiti\, SLP\; - \; Mean\, Tahiti\, SLP}{Standard\, Deviation\, Tahiti}$$

$$Standardized\, Darwin\, SLP = \frac{Actual\, Darwin\, SLP\; - \; Mean\, Darwin\, SLP}{Standard\, Deviation\, Darwin}$$

$$Monthly\, Standard\, Deviation = \sqrt{\frac{\sum(Standard\, Tahiti - Standard\, Darwin)^2}{N}}$$

Wardlaw et al. consider an ENSO episode occurring when the 5-month moving average of SOI remains below -0.5 for more than 5 consecutive months.

The purpose of the ENSO influence analysis in this study is to investigate whether the Red Cross might be provided with a simple method to anticipate if an approaching season might be wetter than normal. The frequency analysis approach, which requires complex analysis and provides an indirect output, was discarded, and a direct comparison with the SOI records was preferred. The SOI records are distributed by the NOAA, from 1951 to 2012. Applying the approach proposed by Wardlaw on the time series available from the Tororo rain gauge, between 1951 and 1983 just three ENSO events were measured, not enough to perform a statistical analysis.

A simple seasonal averaging was used instead, following the approach used by Eltahir in 1996 to study the effect of ENSO on the Nile River flow (Eltahir, 1996). Each year was divided in four seasons: March-April-May (MAM), June-July-August (JJA), September-

October-November (SON), and December-January-February (DJF). The precipitation was cumulated on the season; the SOI was averaged on the season. The correlation between averaged SOI and cumulated precipitation was investigated, considering: (1) no delay in the ENSO effect, (2) one-season delay, (3) two-season delay and (3) three-season delay. None of the combinations resulted in a significant correlation coefficient. The results are shown in Annex 2, 3, 4 and 5.

5.2 Results

A significant correlation was not observed in any of the ENSO-precipitation combinations considered. This result does not prove that ENSO does not have an influence on the climate of the Manafwa River basin; it means that the influence was not directly observable at the local scale in this study. Three possible explanations can be considered:

1. The effects of ENSO in Eastern Uganda are small. The studies referenced are focused on larger geographical areas, like Eastern Equatorial Africa or Lake Victoria. It is possible that the measured influence can only be seen at multi-national scale.
2. The effect of the ENSO is not observable with one point source of rainfall information because the noise due to local anomalies is greater than the main precipitation signal. To make a correct and consistent analysis the precipitation values from different point sources should be averaged, to be sure to mitigate the local anomalies. In order to assess if the precipitation information source is a significant problem, a similar analysis has been carried out in the short term with the TRMM data on the basin, but the result is analogous to prior analyses. Nevertheless, the period covered by the TRMM data is too short to consider the analysis fully reliable and the possibility that the lack of consistent ground measurements is the cause of the missing correlation remains a viable explanation.
3. The signals considered in this analysis are just two: the seasonal Inter-Tropical Convergence Zone (generating wet and dry seasons) and the ENSO. It is possible that other major climate patterns have a significant influence on Eastern Ugandan rainfall, like monsoons or the Madden-Julian Oscillation.

5.3 Contribution of ENSO and the SOI to flood forecasting

Although more detailed studies can be done to understand how ENSO impacts local climate, at this time the Ugandan Red Cross cannot use the SOI measures to anticipate the trend for the following season with reasonable confidence. In case further, more complex, studies reveal a correlation between the ENSO and the precipitation in the Manafwa River basin, it will be necessary to find a simple and feasible way to exploit the information. The example of the Western Africa's flood warning mechanism used by the Red Cross in 2008 showed how crucial the managing and presentation of seasonal forecasts is and how important it is to provide clear, deterministic information. Nevertheless, the Western Africa's case presented also another important resource: the existing collaboration between the Red Cross/Red Crescent Climate Center, the African Center for Meteorological Application for Development (ACMAD), and the International Research Institute for Climate and Society (IRI) at Columbia University. ACMAD and IRI already have the instruments to issue professional and reliable seasonal forecasts and the resource can be used in Eastern Africa as it is used in Western Africa. The limitations due to a large geographical and temporal scale and the probabilistic nature of the forecasts cannot be neglected, but the resource can be effectively used if coupled with the local, deterministic flood early warning system.

6 Conclusion

6.1 Results obtained and their importance

The primary objective of this work was to select and process the precipitation data necessary to run the hydrological model of the Manafwa River for the Red Cross flood early warning system. Because of a lack of ground measurements, the model was run with satellite precipitation estimates. After a consideration of the technical characteristics and of the previous performance of the different available products, the Tropical Rainfall Measuring Mission records were selected. The daily precipitation estimates, product 3B42, were processed to obtain an average daily value for every sub basin in the basin.

The precipitation data processing for the model was not the only objective of this work. A general analysis of the rainfall characteristics in the region was conducted and important conclusions were found.

(1) An analysis of the rainfall trends in the recent years indicated that the average precipitation in the basin is decreasing, making the region on average drier. The high-intensity events are more rare, but more intense. These observations can partially explain the increase of flood frequency and magnitude, despite the decrease of the average precipitation: a drier soil has a lower hydraulic conductivity; when a rainfall event with high intensity occurs the portion of rainfall transformed in runoff is higher and generates a larger flow downstream. The hypothesis can be supported observing how several of the recent floods occurred at the beginning of the wet season.

(2) The possible influence of the El Niño Southern Oscillation on the precipitation was assessed. The Southern Oscillation Index (SOI) and the precipitation recorded by the rain gauge in Tororo were compared, but no evident correlation was found. The result is that at the present time the observation of the SOI cannot contribute in a direct and reliable forecast of the future precipitation.

6.2 Proposed development of the project

Today the hydrological model is able to predict the flooded areas with a given precipitation distribution on the basin. The objective is to make a flood warning system capable of automatically downloading precipitation forecasts to the hydrological model and returning flood risk maps. In the academic years 2013/2014 and 2014/2015 the Massachusetts Institute of Technology's Master in Environmental and Water Quality Engineering will propose the completion of the flood early warning system as a project for the new students of the course.

The system will be based on precipitation forecasts in order to give the Red Cross enough time to intervene. The precipitation forecasts can be provided by the Uganda Department of Meteorology, able to produce local predictions, or by international forecasts producers. The warning system will be able to automatically access the data, and download it on a Red Cross/Red Crescent Climate Center's server every day. The server will also host the hydrological model. When the forecasts are available, the model will run automatically once a day. The results will be elaborated by software capable of distinguishing the difference between a normal flow within the river banks, and a flow on normally dry areas outside of the river banks. If the result is out of normality, three actions are automatically taken:

1. A SMS text is send to RC/RC Climate Center staff and other stakeholders to communicate a situation of potential risk.
2. A customized map is automatically generated, showing the areas at risk, with a color gradient representing the water depth. A brief report can also be generated with useful information for the Red Cross (affected villages, streets, warehouses, etc.)
3. An automatic email message is sent to the RC/RC Climate Center staff, containing the report and the map.

At this point the Climate Center will initiate a standardized procedure to alert local authorities, local Red Cross offices, local volunteers, and to communicate the actions to undertake.

The model results will be compared with local measures, to ensure the consistency of the model output. The consistency of the model is essential to avoid false alarms, causing money losses, people doubting the reliability of the system, or missing a flood event prediction. The precipitation forecasts can be checked with rain gauges, the flow estimates with river gauges. The detailed description of the proposed system is in Annex 6 – Flood warning system scheme.

An interesting communication method might be the 3G Internet network. Despite the poor quality of the power network, the cell phone services and the 3G data network are reliable and cover almost the entire Ugandan territory, with exception of the forests (MTN Uganda, 2009).

Finally, considering that the power network is not reliable and that power shortages occur frequently, all the electric instrumentation must be protected with uninterrupted powers supplies and possibly portable generators.

6.3 Recommendations

The goals of subsequent work should include: improving the warning system design, installing the instrumentation, developing the necessary interfacing software, and assessing the availability of support from the necessary partners. Collaboration with the MIT's Humanitarian Response Laboratory may assist the Red Cross in developing the standard emergency procedures to undertake in case of flood forecast.

In order to make the hydrological model more accurate, it is advisable to install ground instrumentation to measure precipitation and river flow. The Red Cross has indicated interest in purchasing and installing instrumentation, but advice from MIT is desirable to ensure appropriate instrument selection, define the locations for installation, install the instruments and integrate them in the flood warning system. Furthermore, it would be interesting to understand what problems have been making the rain gauges in Bududa and Buginyanya unreliable so that these might be corrected.

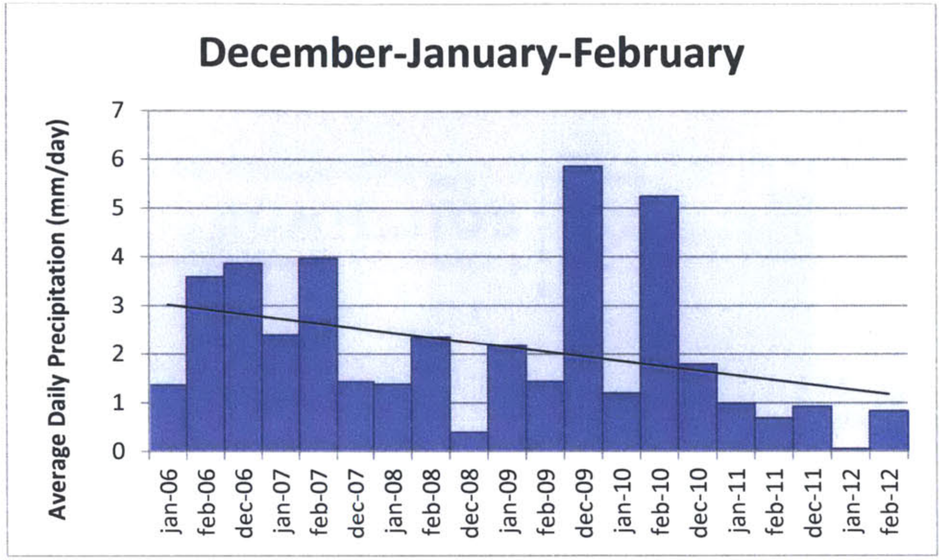
A second objective for the future is to find a reliable precipitation forecast source and integrate it in the flood warning system. The hydrological model was designed to work with TRMM recorded data and it should be tested and calibrated using the new source of rainfall forecasts.

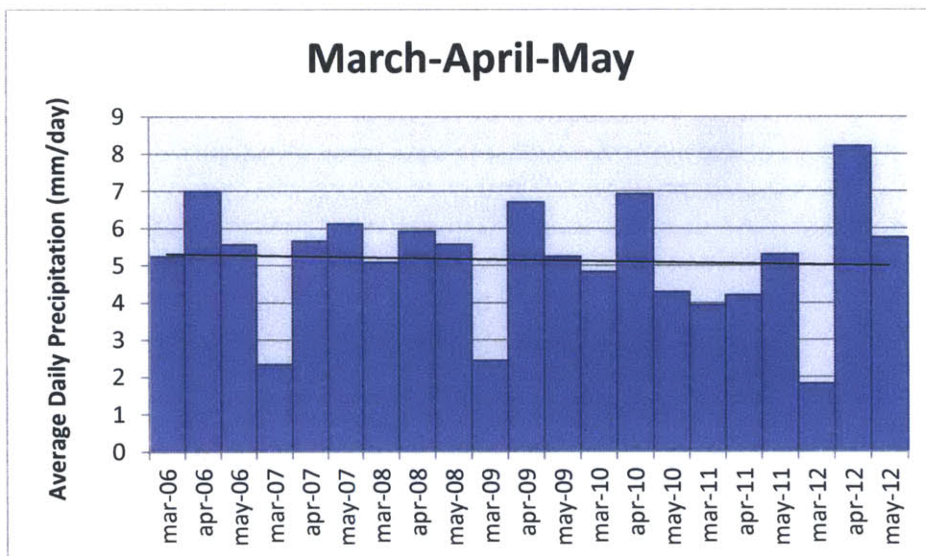
Although a significant influence of El Niño was not observed in the precipitation records on the Manafwa River basin, further studies can be developed to better understand the role of the ENSO in the local climate and the effect that other major climate patterns might have on precipitation in Eastern Uganda.

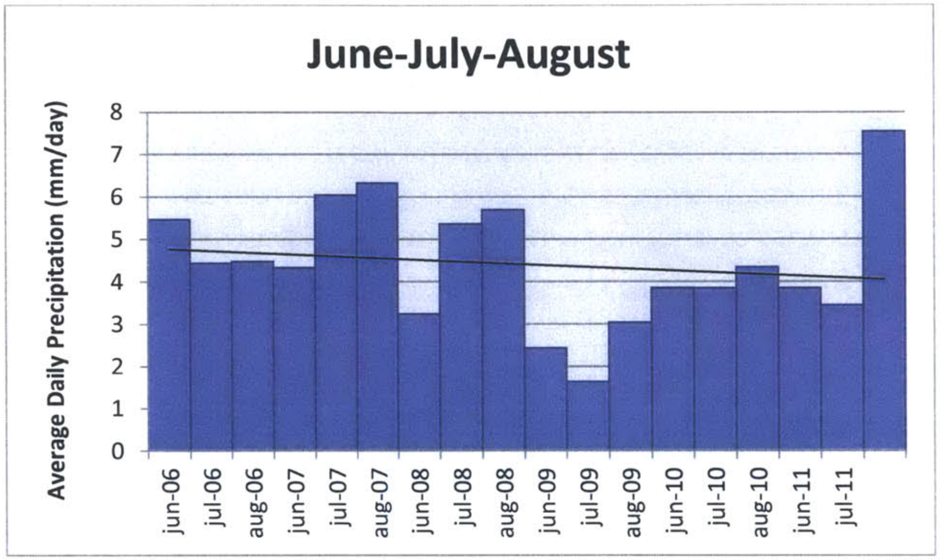
Finally, the main recommendation for the future is to make the flood warning system for the Manafwa River basin work properly. In order to complete the flood warning system, different stake holders will be involved and a correct coordination of them will be vital. The Red Cross has experience in this field and, when the correct functionality is established, the opportunity would then exist to export the same model to other basins in Uganda under the coordination of the RC/RC Climate Center in Kampala.

The present work has been developed to make future development of the flood warning system possible; it will be successful if the flood early warning system is established and the life quality of the Manafwa River communities will be improved.

Annex 1- Precipitation trends in the four different seasons






June-July-August
Average Daily Precipitation (mm/day)
0
1
2
3
4
5
6
7
8
jun-06
jul-06
aug-06
jun-07
jul-07
aug-07
jun-08
jul-08
aug-08
jun-09
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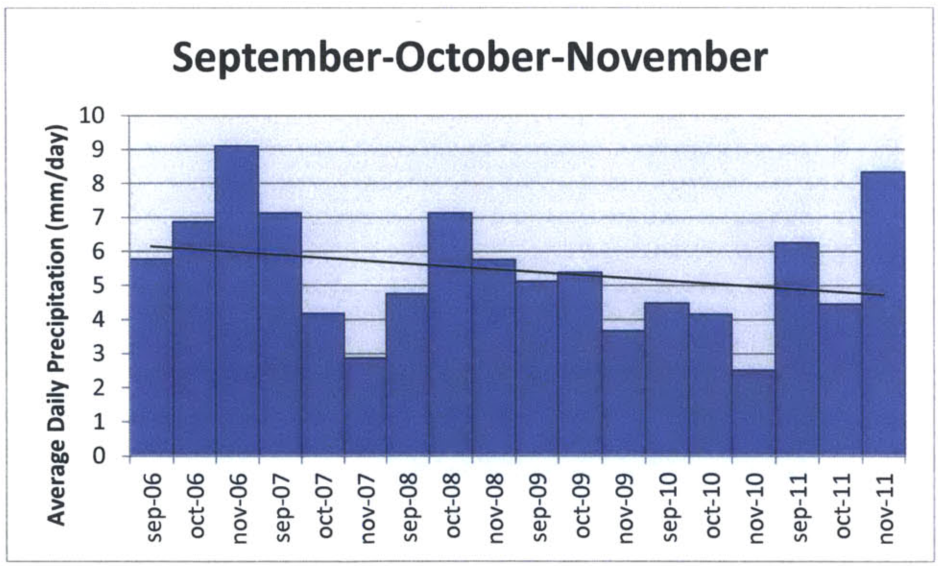
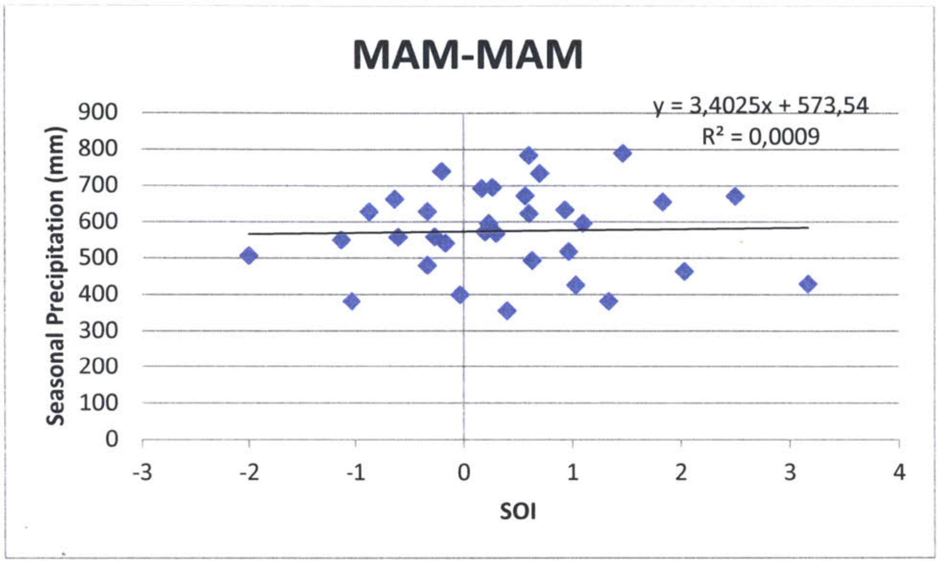
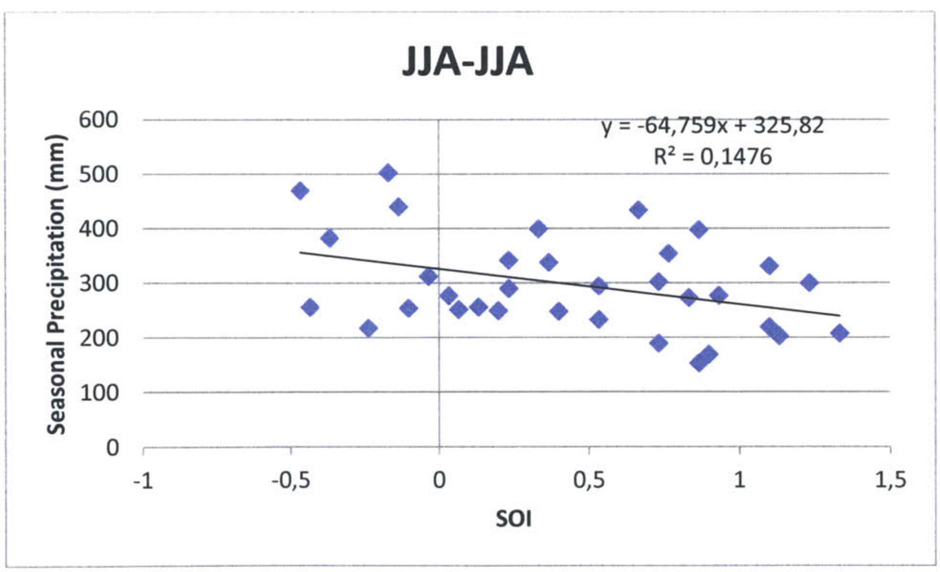
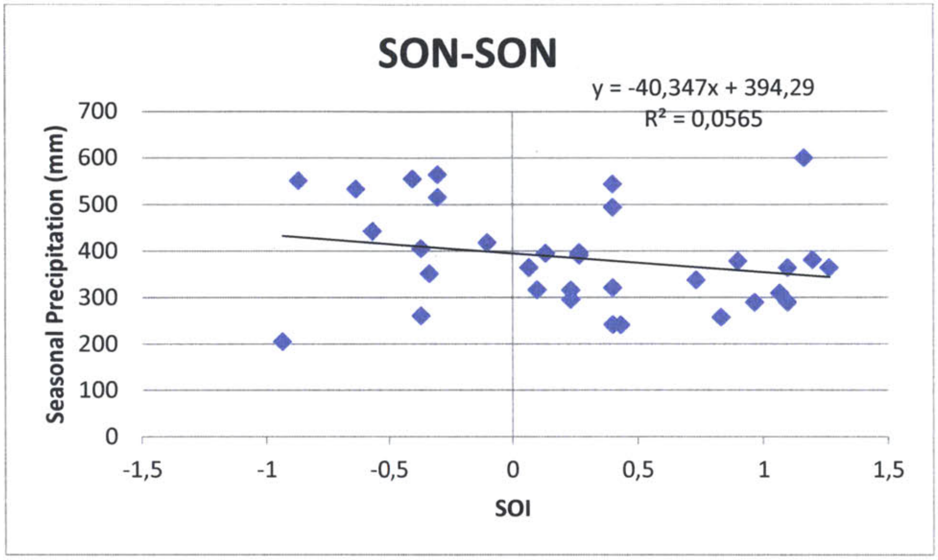
jun-10
jul-10
aug-10
jun-11
jul-11

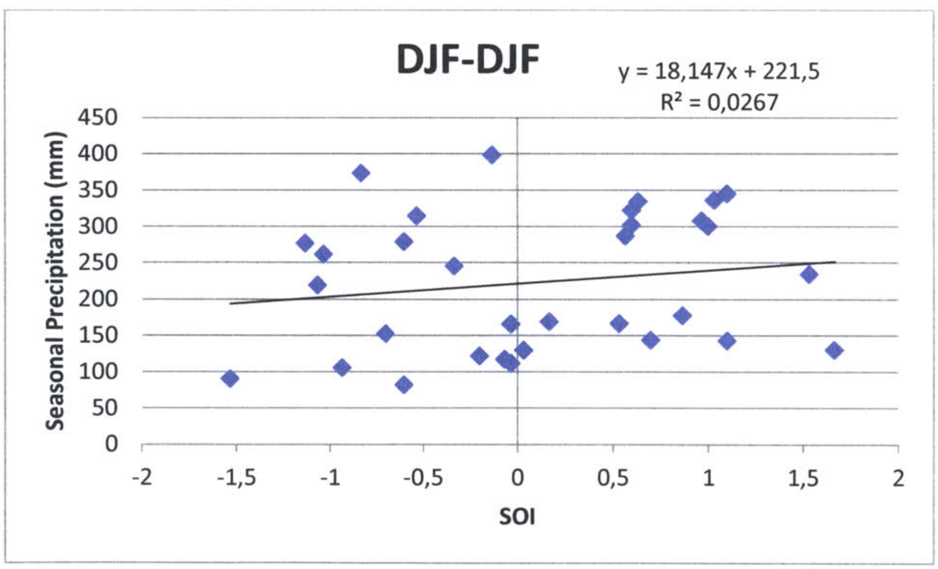

September-October-November
Average Daily Precipitation (mm/day)
0
1
2
3
4
5
6
7
8
9
10
sep-06
oct-06
nov-06
sep-07
oct-07
nov-07
sep-08
oct-08
nov-08
sep-09
oct-09
nov-09
sep-10
oct-10
nov-10
sep-11
oct-11
nov-11

Annex 2 – Rain gauge rainfall and SOI correlation with no delay

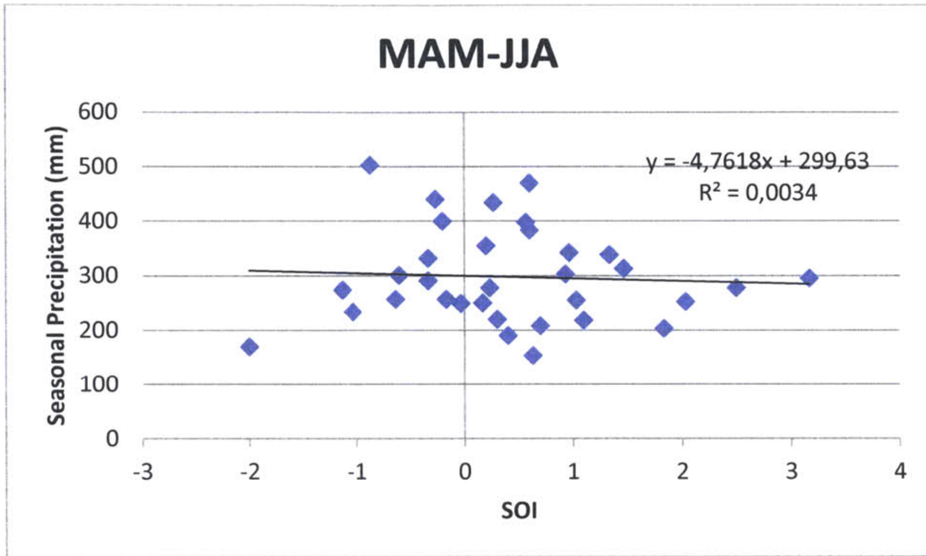


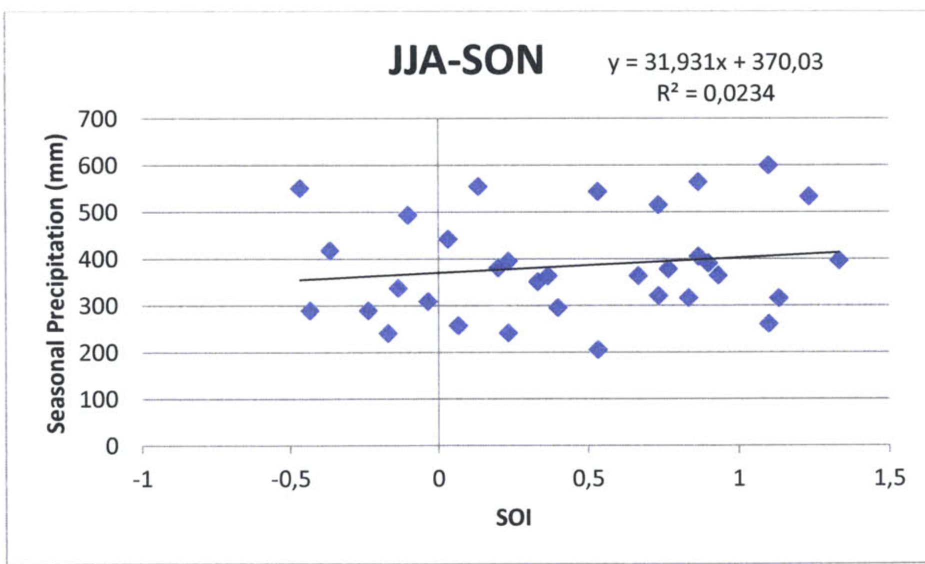


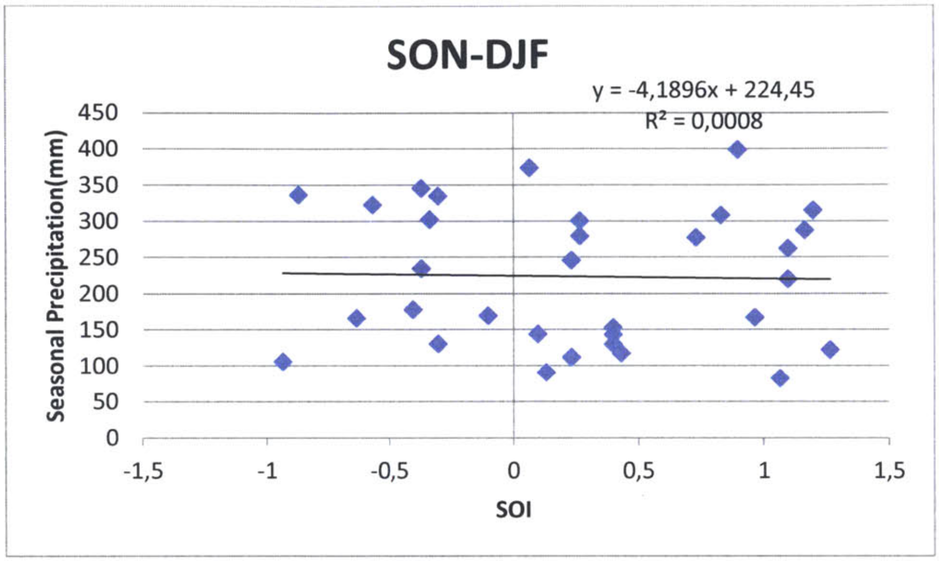

SON-SON
y = -40,347x + 394,29
R² = 0,0565
Seasonal Precipitation (mm)
700
600
500
400
300
200
100
0
-1,5
-1
-0,5
0
0,5
1
1,5
SOI

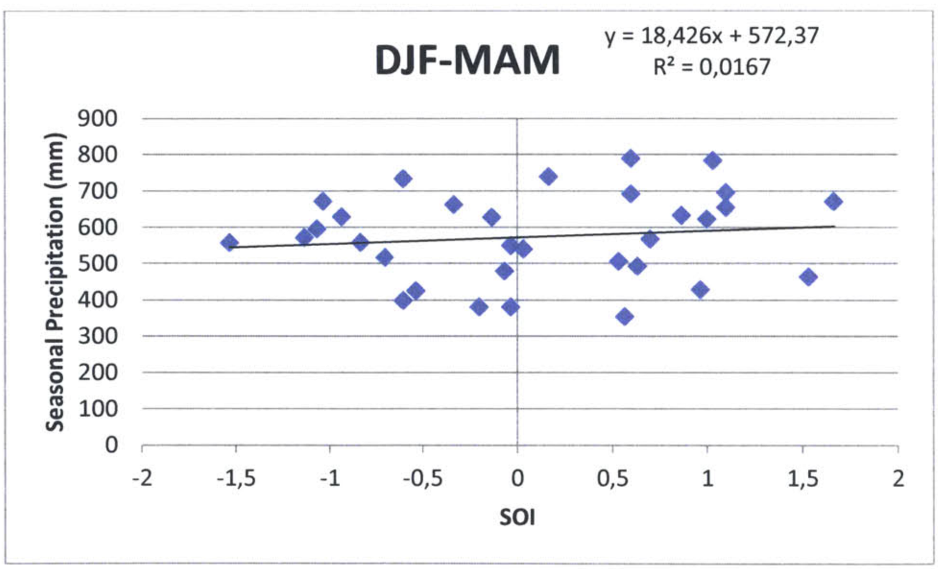

DJF-DJF
y = 18,147x + 221,5
R² = 0,0267
Seasonal Precipitation (mm)
450
400
350
300
250
200
150
100
50
0
-2
-1,5
-1
-0,5
0
0,5
1
1,5
2
SOI

Annex 3 – Rain gauge rainfall and SOI correlation with one-season delay in precipitation response

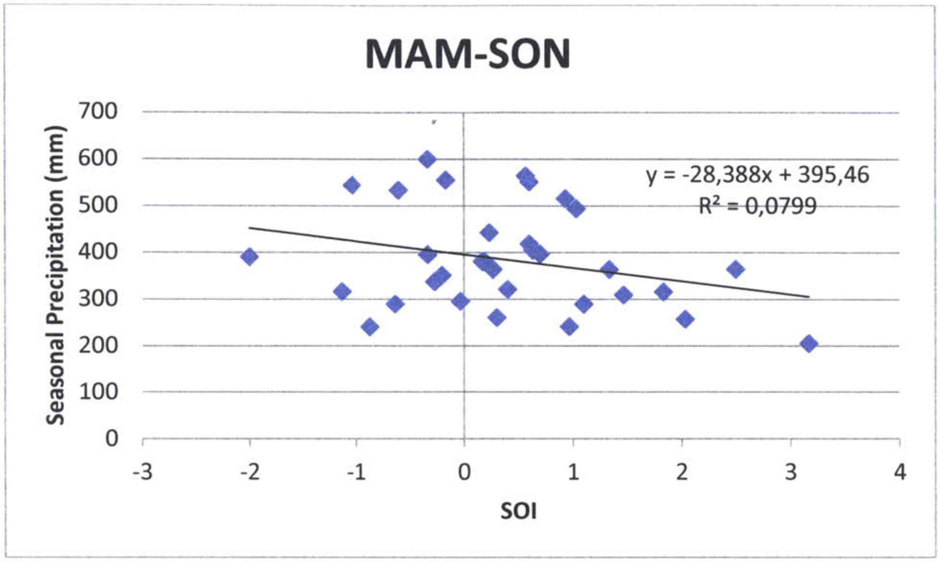


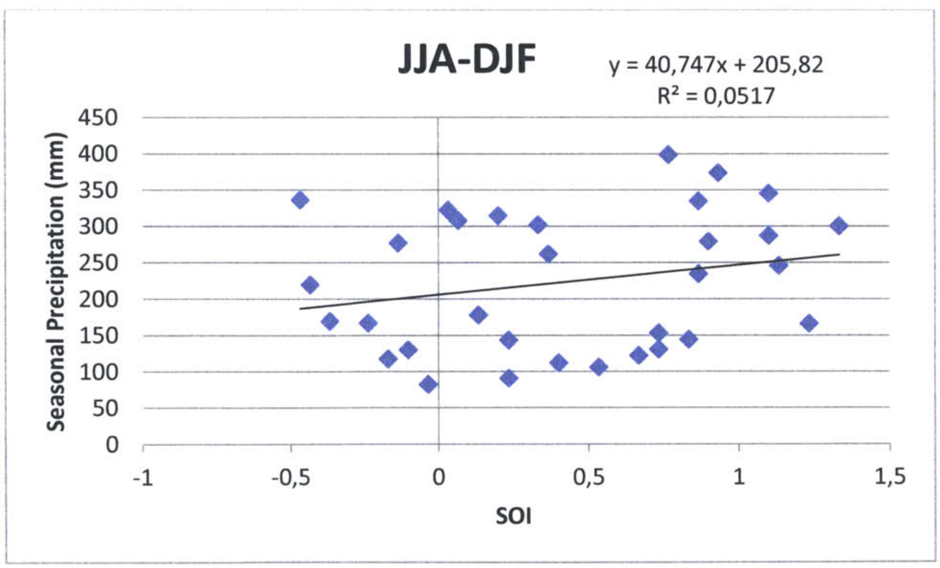


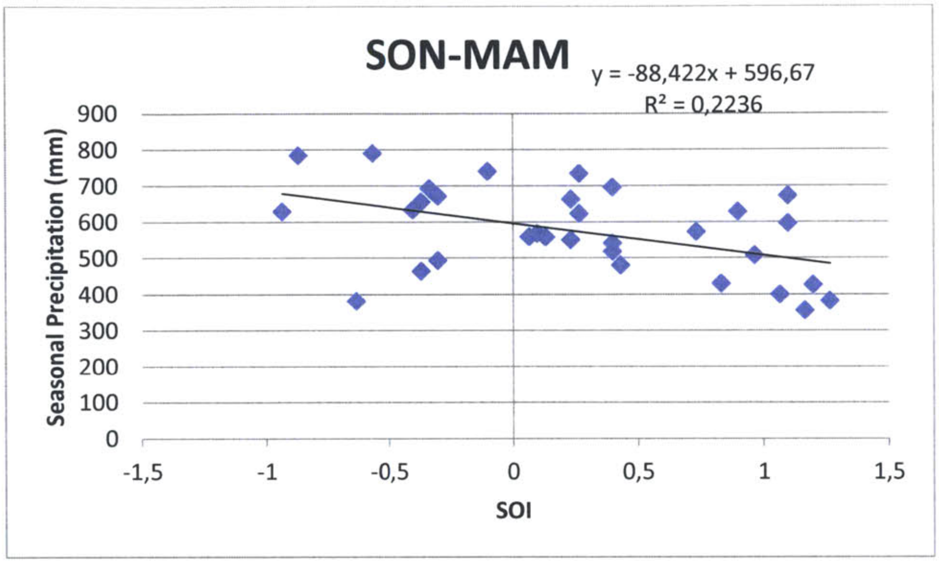

SON-DJF
y = -4,1896x + 224,45
R² = 0,0008
Seasonal Precipitation(mm)
450
400
350
300
250
200
150
100
50
0
-1,5
-1
-0,5
0
0,5
1
1,5
SOI

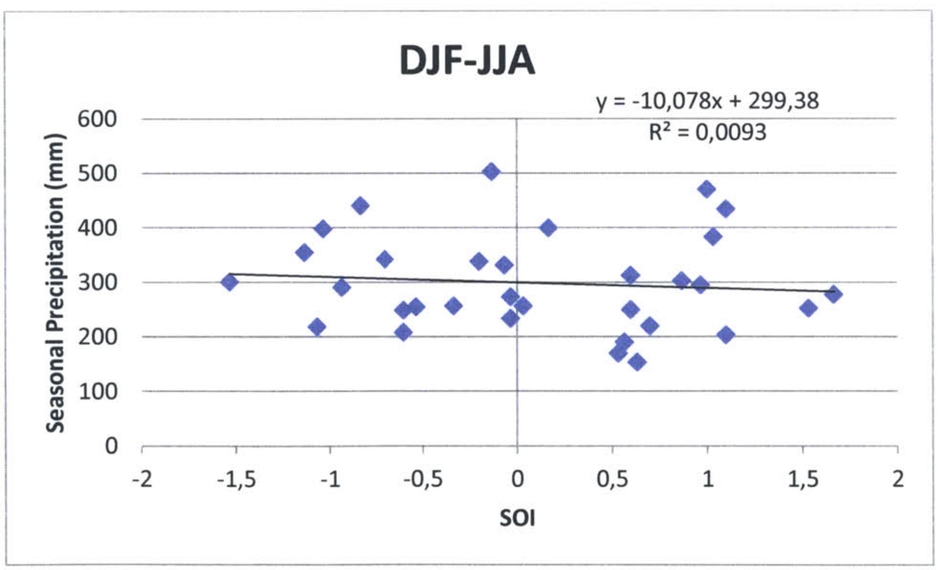

DJF-MAM
y = 18,426x + 572,37
R² = 0,0167
Seasonal Precipitation (mm)
900
800
700
600
500
400
300
200
100
0
-2
-1,5
-1
-0,5
0
0,5
1
1,5
2
SOI

Annex 4 – Rain gauge rainfall and SOI correlation with two-season delay in precipitation response

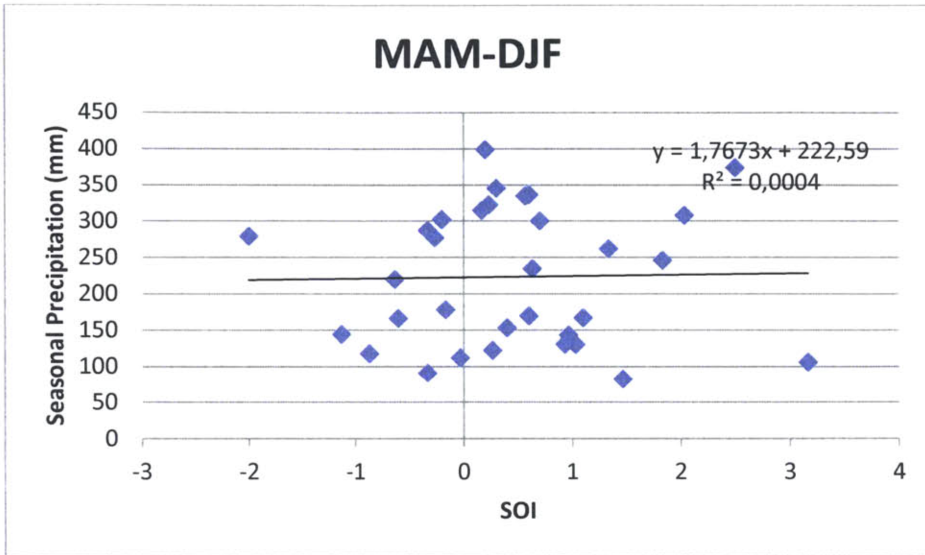


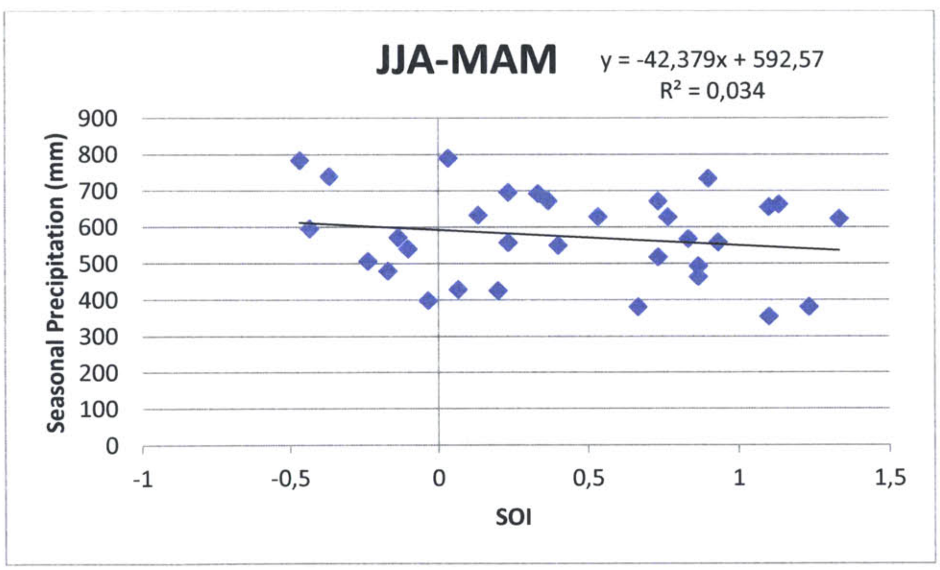


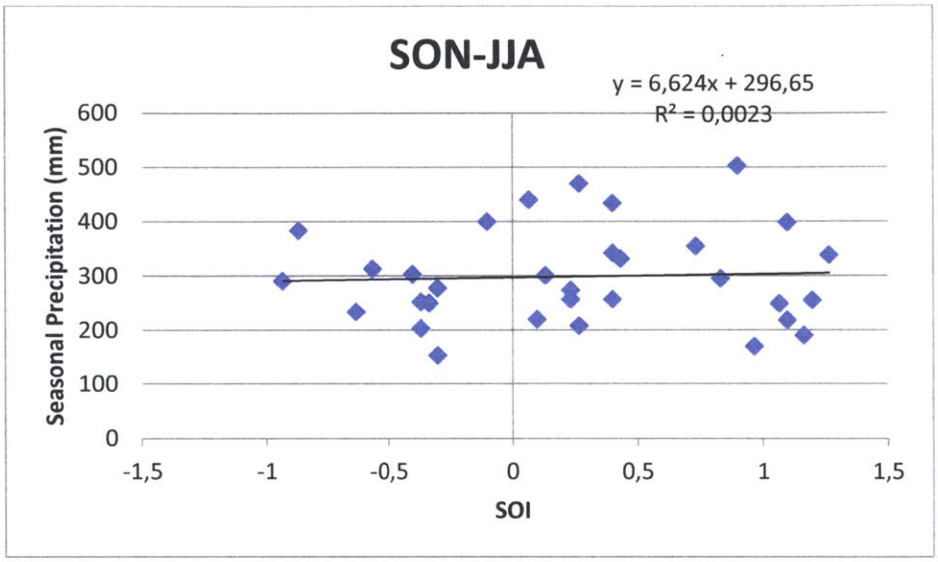

SON-MAM
y = -88,422x + 596,67
R² = 0,2236
Seasonal Precipitation (mm)
900
800
700
600
500
400
300
200
100
0
-1,5
-1
-0,5
0
0,5
1
1,5
SOI

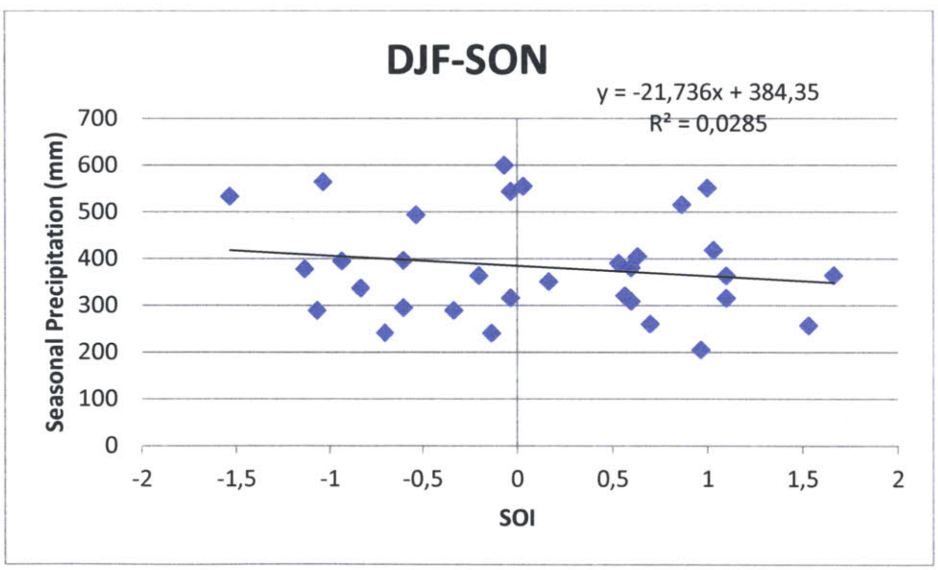

DJF-JJA
y = -10,078x + 299,38
R² = 0,0093
Seasonal Precipitation (mm)
600
500
400
300
200
100
0
-2
-1,5
-1
-0,5
0
0,5
1
1,5
2
SOI

Annex 5 – Rain gauge rainfall and SOI correlation with three-season delay in precipitation response

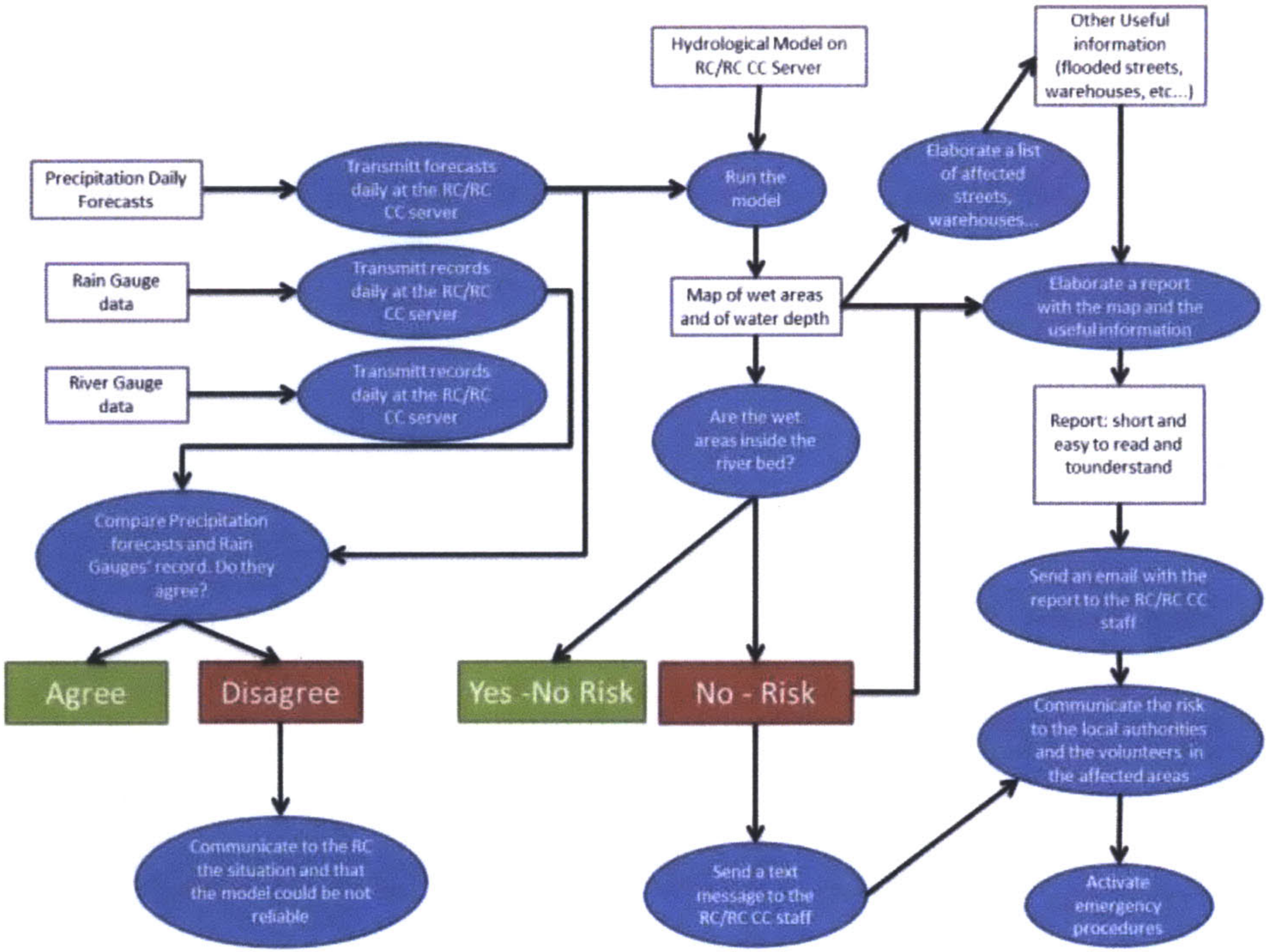





SON-JJA
y = 6,624x + 296,65
R² = 0,0023
Seasonal Precipitation (mm)
600
500
400
300
200
100
0
-1,5
-1
-0,5
0
0,5
1
1,5
SOI


DJF-SON
y = -21,736x + 384,35
R² = 0,0285
Seasonal Precipitation (mm)
700
600
500
400
300
200
100
0
-2
-1,5
-1
-0,5
0
0,5
1
1,5
2
SOI

Annex 6 – Flood warning system scheme



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